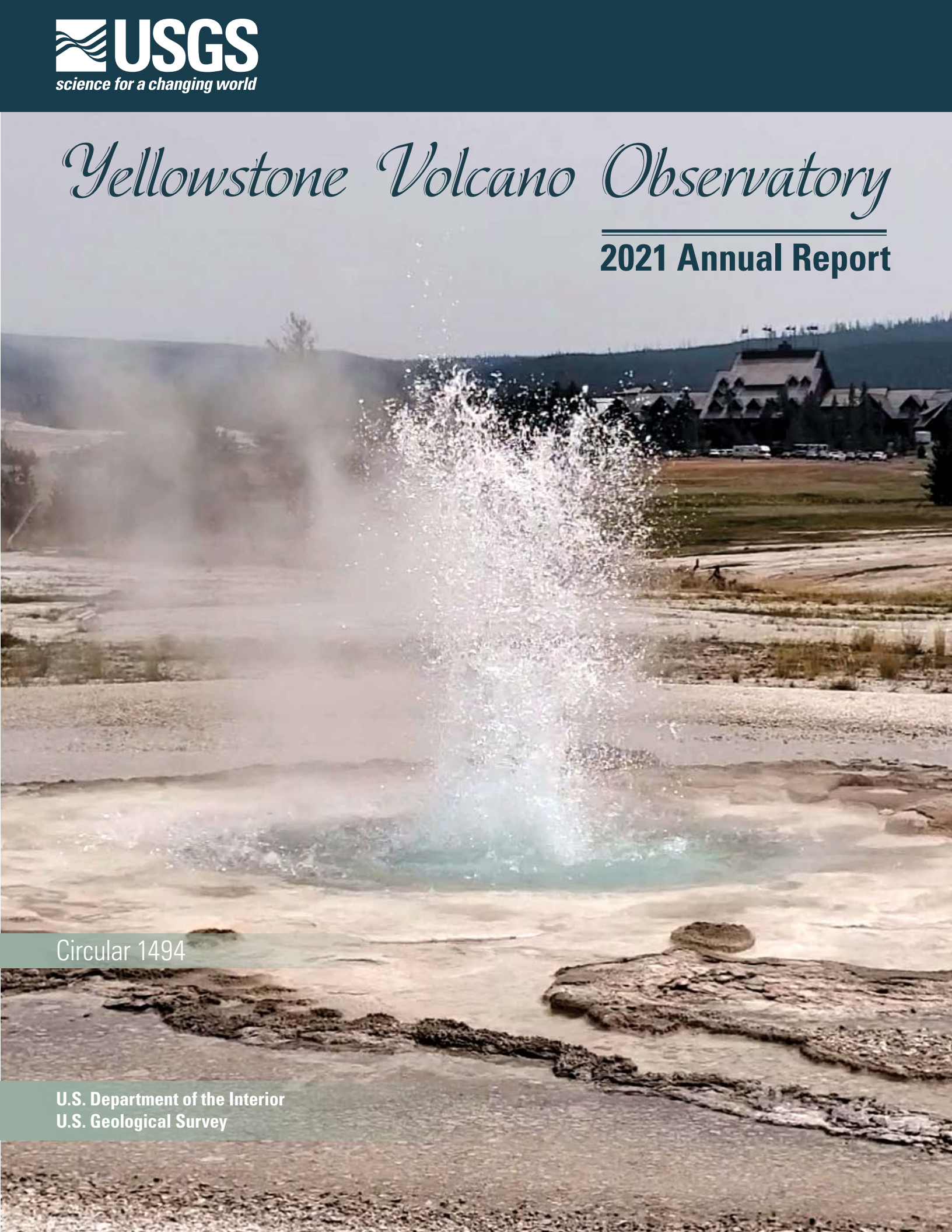


# *Yellowstone Volcano Observatory*

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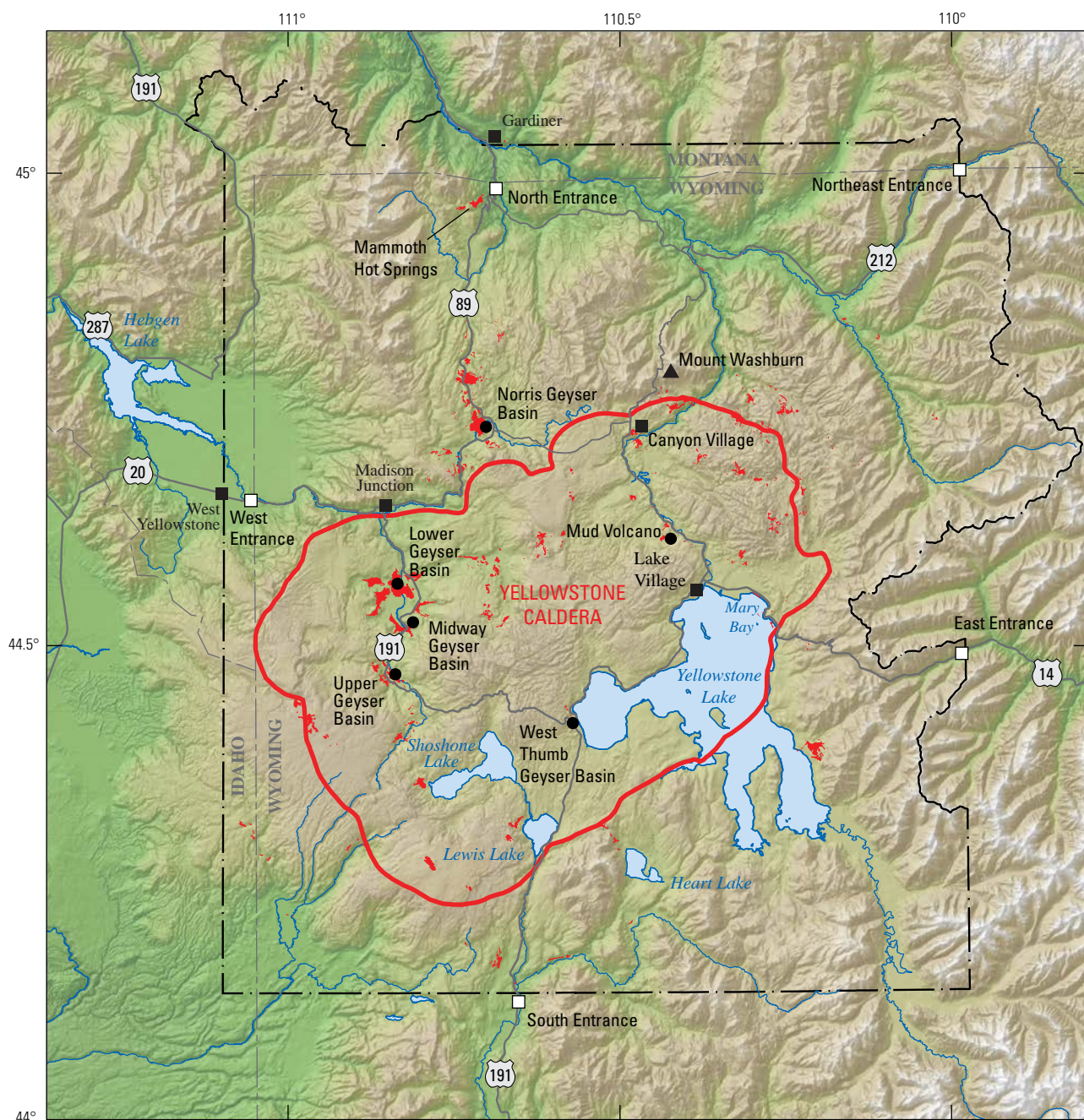
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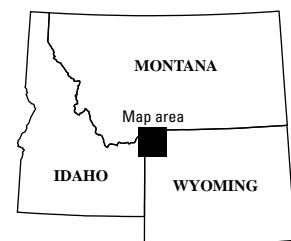
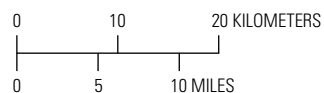
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Base from 30-meter National Elevation Dataset



Location map showing thermal areas (in red) and noteworthy geographic features in the Yellowstone National Park region. The red line marks Yellowstone Caldera.

**Cover.** Photograph of Sawmill Geyser in eruption on July 23, 2021. Old Faithfull Inn is in the background. National Park Service photograph by Morgan Nasholds.

**Facing page.** Photograph of Grand Prismatic Spring by Cory Hurd, used with permission.



The background of the cover is a photograph of a geothermal landscape. In the foreground, there are intricate, brownish-yellow mineral terraces. A layer of white steam or smoke drifts across the middle ground. Behind the steam is a dense forest of dark evergreen trees. The top of the image shows a blue sky with a few white clouds. At the very top, there is a decorative curved band with a dark blue outer edge and a light green inner edge.

# *Yellowstone Volcano Observatory*

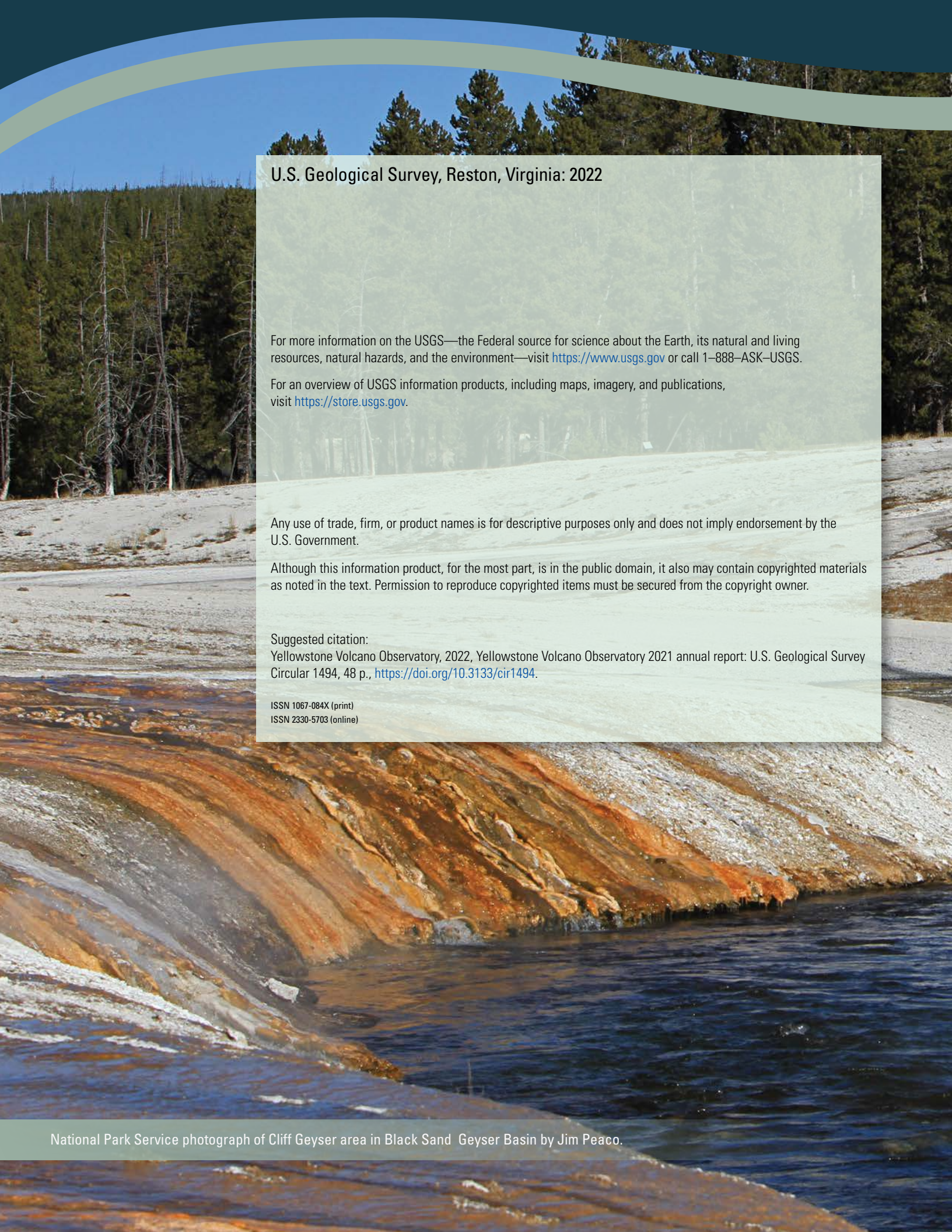
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**2021 Annual Report**

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## Contents

Introduction.....	1
YVO Activities .....	1
Seismology.....	4
Overall Seismicity in 2021 .....	4
Seismic Studies of Geyser Systems .....	4
Geodesy.....	8
Overall Deformation in 2021 .....	8
Continuous GPS Results .....	13
Semipermanent GPS Results .....	13
InSAR.....	14
Geochemistry.....	14
Summary of Geochemistry Activities in 2021 .....	14
Gas Emissions.....	14
Water Sampling.....	19
Geology.....	19
Summary of Geology Activities in 2021 .....	22
Understanding the Recent Volcanic History of the Yellowstone Region.....	22
Geologic Mapping in Yellowstone Caldera.....	23
Geology of Mount Everts .....	24
Sour Creek Dome Remapping.....	26
Mapping Twin Buttes Hydrothermal Explosion Crater in Lower Geyser Basin.....	27
Hydrothermal Travertine Within Yellowstone Caldera .....	27
Sample Collection Database.....	27
Yellowstone Lake Studies.....	29
Summary of Yellowstone Lake Studies in 2021 .....	29
Explosion Deposits in Lake-Bottom Sediments .....	29
Analyses of Paleo-environmental Conditions from Yellowstone Lake Sediment Core .....	32
New Sediment Cores from Yellowstone Lake .....	32
Heat Flow Studies .....	32
Summary of Heat Flow Studies in 2021 .....	33
Thermal-Infrared Remote Sensing .....	33
Recognition of Previously Unmapped Thermal Areas.....	37
Chloride Flux Monitoring.....	38
Geysers and Hot Springs .....	39
Summary of Geyser Activity and Research in 2021 .....	39
Steamboat Geyser .....	39
Sawmill Geyser.....	41
Tracking Changes in Thermal Features.....	41
Structure and Composition of Geyser Cones .....	43
Hydrothermal Feature Survey.....	43
Communications and Outreach .....	45
Online Geology of Yellowstone Map.....	45
Summary.....	46
2021 Publications .....	46
References Cited.....	47



## Figures

1. Map of earthquakes that occurred during 2021 in the Yellowstone National Park region .....	5
2. Photograph showing seismic nodes deployed around Doublet Pool in Upper Geyser Basin .....	8
3. Map of Global Positioning System stations showing the deformation observed in Yellowstone National Park in 2021 .....	9
4. Map of semipermanent Global Positioning System stations showing changes observed in Yellowstone National Park from 2020 to 2021 .....	13
5. Interferogram created from data collected on September 22, 2020, and September 17, 2021, over the Yellowstone region by the Sentinel-1 satellite system .....	15
6. Map of log soil CO <sub>2</sub> flux at the Obsidian Pool thermal area in Yellowstone National Park .....	16
7. Time-series plots of 30-minute average gas ratios and meteorological parameters measured at the multicomponent gas analyzer system station MUD during 2021 .....	17
8. Rose diagrams showing joint frequency distributions of 30-minute average wind speed and gas ratios with wind direction measured at the multicomponent gas analyzer system station MUD from July through December 2021 .....	18
9. Photograph of Colloidal Pool in Norris Geyser Basin .....	19
10. Shaded-relief map of Yellowstone Caldera showing the age and location of intra-caldera rhyolites that erupted after the Lava Creek Tuff .....	22
11. Map showing the most detailed geologic maps that exist for Yellowstone National Park .....	23
12. Photograph of Mount Everts, located on the northern boundary of Yellowstone National Park .....	24
13. Geologic maps of the northern part of Mount Everts in north-central Yellowstone National Park .....	25
14. Geologic map of the Sour Creek dome area in the eastern part of Yellowstone Caldera .....	26
15. Map and oblique view of color shaded relief of the Twin Buttes hydrothermal explosion crater in Lower Geyser Basin .....	28
16. Photograph of a horizontally bedded travertine terrace deposit near Firehole Lake in the Lower Geyser Basin of Yellowstone National Park .....	29
17. Bathymetric map of Yellowstone Lake .....	30
18. Schematic diagram illustrating a large, alkaline-chloride hydrothermal explosion in Yellowstone Lake generated by a sudden pressure drop at the surface .....	31
19. Photograph of pore waters from Yellowstone Lake sediment cores collected in August 2021 .....	32
20. Landsat-8 nighttime thermal-infrared image of Yellowstone National Park from January 9, 2021 .....	36



21.	Satellite images of previously unidentified thermal areas in Yellowstone National Park .....	37
22.	Photograph of the Lewis River monitoring site located downstream from the Lewis Lake outlet in Yellowstone National Park.....	38
23.	Pie diagram and boxplot showing the 2021 chloride flux for the four major rivers that drain the Yellowstone National Park region .....	39
24.	Photograph of Steamboat Geyser displaying steam emissions that are characteristic of periods between major water eruptions.....	40
25.	Photograph of Sawmill Geyser in eruption on July 23, 2021.....	41
26.	Satellite images of an unnamed thermal feature in the Three River Junction thermal area, southwest Yellowstone National Park.....	42
27.	Photographs of Castle and Giant Geysers in Upper Geyser Basin of Yellowstone National Park.....	43
28.	Screenshots of three-dimensional models of Castle and Giant Geysers constructed using structure-from-motion photogrammetry.....	44
29.	Screenshot of the online Geology of Yellowstone Map showing some of the layers that were added in 2021.....	45

## Tables

1.	Temperature, pH, and conductivity measurements at Colloidal Pool in Norris Geyser Basin, Yellowstone National Park.....	19
2.	Total geothermal radiative power output from Yellowstone National Park in the previous 5 years.....	37

## Sidebars

Volcanic Hazards in the Yellowstone Region .....	2
What is the Yellowstone Volcano Observatory?.....	3
Seismicity in Yellowstone Plateau .....	6
Monitoring Geodetic Change in the Yellowstone Region.....	10
Geochemical Monitoring in Yellowstone National Park.....	16
Geology of the Yellowstone Plateau .....	20
Monitoring Thermal Changes at Yellowstone National Park.....	34





National Park Service photograph of Cupid Spring at Mammoth Hot Springs by Diane Rankin.



# Yellowstone Volcano Observatory

By the Yellowstone Volcano Observatory<sup>1</sup>

## 2021 Annual Report

### Introduction

The Yellowstone Volcano Observatory (YVO) monitors volcanic and hydrothermal activity associated with the Yellowstone magmatic system, carries out research into magmatic processes occurring beneath Yellowstone Caldera, and issues timely warnings and guidance related to potential future geologic hazards (see sidebar on volcanic hazards on p. 2). YVO is a collaborative consortium made up of the U.S. Geological Survey (USGS), Yellowstone National Park, University of Utah, University of Wyoming, Montana State University, UNAVCO, Wyoming State Geological Survey, Montana Bureau of Mines and Geology, and Idaho Geological Survey (see sidebar on YVO on p. 3). The USGS arm of YVO also has the operational responsibility for monitoring volcanic activity in the Intermountain West of the United States, including Arizona, New Mexico, Utah, and Colorado.

This report summarizes the activities and findings of YVO during the year 2021, focusing on the Yellowstone volcanic system. Highlights of YVO research and related activities during 2021 include

- Deployments of seismometers in Norris Geyser Basin near Steamboat Geyser and in Upper Geyser Basin in the Geyser Hill area to investigate geyser plumbing systems,
- Semipermanent Global Positioning System (GPS) array deployment from May to October,
- Geological studies of post-glacial hydrothermal activity,
- Refining the ages of Yellowstone volcanic units and updating existing maps of geologic deposits,
- Installation of a new continuous gas monitoring station near Mud Volcano,

- Sampling of thermal waters around Yellowstone National Park to monitor water chemistry over space and time, and
- Assessment of thermal output based on satellite imagery and chloride flux in rivers.

Steamboat Geyser, in Norris Geyser Basin, continued the pattern of frequent eruptions that began in 2018 with 20 water eruptions in 2021—a significant decrease from the 48 eruptions that occurred in both 2019 and 2020. The variation in activity at Steamboat Geyser is typical for Yellowstone National Park hydrothermal systems, where many geysers experience alternating periods of frequent and infrequent eruptions.

Patterns of both seismicity and deformation in 2021 were similar to those in 2020. Total seismicity—2,773 located earthquakes—was elevated compared to the 1,722 earthquakes located in 2020, but not significantly outside the historical average of about 1,500–2,500 earthquakes per year. Deformation patterns during 2021 showed trends that continued from previous years. Overall subsidence of the caldera floor, ongoing since late 2015 or early 2016, continued at rates of a few centimeters (1–2 inches) per year, whereas deformation in the Norris Geyser Basin area was below detection levels. Satellite deformation measurements indicate the possibility of slight uplift amounting to about 1 centimeter (less than 1 inch) along the north caldera rim, south of Norris Geyser Basin. The deformation is similar to that which occurred in the late 1990s.

Throughout 2021, the aviation color code for Yellowstone Caldera remained at “green” and the volcano alert level remained at “normal.”

### YVO Activities

For the second year in a row, YVO activities were severely limited by the Coronavirus Disease 2019 (COVID-19) pandemic. Field projects were somewhat curtailed or limited in scope, although critical field surveys and instrument maintenance were completed as needed to maintain monitoring networks and continue valuable scientific research projects.

In March 2021, YVO bid a fond farewell to a core member of the team when Deb Bergfeld retired from the USGS after nearly 20 years of service. Deb’s research was focused on the chemical composition of gases emitted in volcanic and geothermal systems,

<sup>1</sup>This report was prepared jointly by members of the Yellowstone Volcano Observatory consortium, including Michael Poland, Daniel Dzurisin, Lauren Harrison, Shaul Hurwitz, Jennifer Lewicki, Blaine McCleskey, Lisa Morgan, Pat Shanks, Mark Stelten, Wendy Stovall, R. Greg Vaughan, and Charles Wicks of the U.S. Geological Survey, Jefferson Hungerford of the National Park Service, Jamie Farrell of the University of Utah, James Mauch and Erin Campbell of the Wyoming State Geological Survey, and Madison Myers, Natali Kragh, Devon Orme, and Ray Salazar of Montana State University. Liz Westby and David Phillips of the U.S. Geological Survey reviewed the report.



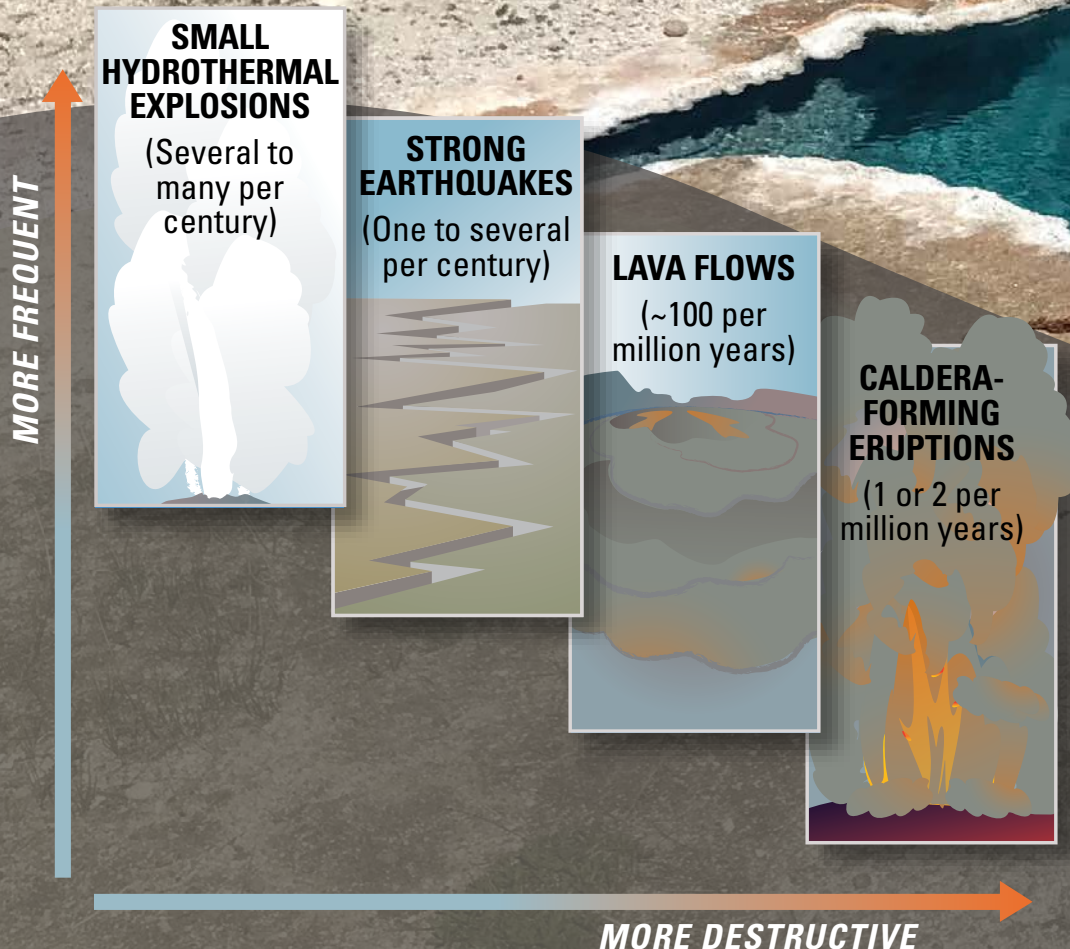
## Volcanic Hazards in the Yellowstone Region

The Yellowstone Plateau in the northern Rocky Mountains of Wyoming, Montana, and Idaho is centered on a youthful, active volcanic system with subterranean magma (molten rock), boiling and pressurized waters, and a variety of active faults. This combination creates a diversity of hazards, but the most catastrophic events—large volcanic explosions—are the least likely to occur.

Over the past 2.1 million years, Yellowstone volcano has had three immense explosive volcanic eruptions that blanketed large parts of the North American continent with ash and debris and created sizable calderas. Yellowstone Caldera, which comprises nearly one third of the land area in Yellowstone National Park, formed 631,000 years ago during the most recent of these large explosive phases. Its formation was followed by dozens of less explosive but massive lava flows, the last of which erupted 70,000 years ago.

Tectonic extension of the western United States is responsible for large and devastating earthquakes in the Yellowstone region along the Teton and Hebgen Faults. Most recently, a devastating magnitude 7.3 earthquake in 1959 killed 28 people, and a strong magnitude 6.1 earthquake near Norris Geyser Basin in 1975 was widely felt.

Yellowstone National Park's famous geothermal waters create fabulous hot springs and geysers but occasionally explode catastrophically to create craters found throughout the park. At least 25 explosions that left craters greater than 100 meters (about 300 feet) wide have occurred since the last ice age ended in the Yellowstone region 16,000–13,000 years ago. Much smaller explosions, which leave craters only a few meters (yards) across, happen every few years in the Yellowstone region.



The most destructive hazards in the Yellowstone region, including volcanic explosions and lava flow eruptions, are also the least likely to occur. On human timescales, the most likely hazards are small hydrothermal explosions and strong earthquakes. Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern and others, 2005).

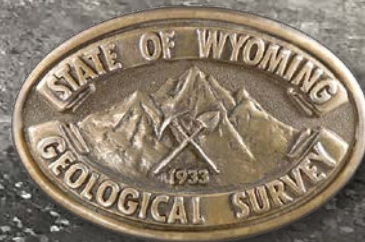


## What is the Yellowstone Volcano Observatory?

The Yellowstone Volcano Observatory (YVO) was formed on May 14, 2001, to strengthen the long-term monitoring of volcanic and seismic unrest in the Yellowstone National Park region. YVO is a “virtual” observatory that does not have an on-site building to house employees. Instead, it is a consortium of nine organizations spread throughout the western United States that collaborate to monitor and study the volcanic and hydrothermal systems of the Yellowstone region, as well as disseminate data, interpretations, and accumulated knowledge to the public. The partnership provides for improved collaborative study and monitoring of active geologic processes and hazards of the Yellowstone Plateau volcanic field, which is the site of the largest and most diverse collection of natural thermal features on Earth, the world’s first national park, and the United States’ first World Heritage Site.

Each of the nine consortium agencies offers unique skill sets and expertise to YVO. The U.S. Geological Survey has

the Federal responsibility to provide warnings of volcanic activity and holds the ultimate authority over YVO operations. Key geophysical monitoring sites were established and are maintained by the University of Utah and UNAVCO. Scientists from these two organizations analyze and provide data to the public as well as carry out research on active tectonic and volcanic processes in the region. Yellowstone National Park is the land manager and responsible for emergency response to natural disasters within the national park boundaries. The Wyoming State Geological Survey, Montana Bureau of Mines and Geology, and Idaho Geological Survey provide critical hazards information and outreach products to their respective citizens. The University of Wyoming and Montana State University support research into the Yellowstone region’s volcanic and hydrothermal activity, as well as the geologic history of the region. YVO agencies also aid and collaborate with scientists outside the consortium.



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GEOLOGICAL SURVEY

USGS  
science for a changing world

MONTANA  
STATE UNIVERSITY



MBMG  
Montana Bureau of Mines and Geology

UNAVCO

THE  
UNIVERSITY  
OF UTAH

UNIVERSITY OF WYOMING

Member agencies of the Yellowstone Volcano Observatory.

Background photograph of a hot spring in Upper Geyser Basin by Cory Hurd, used with permission.



and she applied her expertise to many volcanoes in the United States. In Yellowstone National Park, Deb sampled and analyzed gases from many thermal areas, and the data and interpretations were used to assess the sources of the gases (magma, crustal rocks, organic material, and so on) and the processes that take place between the source and the sampling location at the ground surface. Deb's research was published in many peer-reviewed journals and provides a better understanding of the state of the Yellowstone magmatic system.

## Seismology

Earthquakes have been monitored in the Yellowstone region since the 1970s (see sidebar on seismicity on p. 6–7). The Yellowstone Seismic Network is maintained and operated by the University of Utah Seismograph Stations, which records data from 46 stations in the Yellowstone region. On average, about 1,500–2,500 earthquakes are located in and around Yellowstone National Park every year (most of which are too small to be felt by humans), making the Yellowstone region one of the most seismically active areas in the United States.

### Overall Seismicity in 2021

During 2021, the University of Utah Seismograph Stations located 2,773 earthquakes in the Yellowstone region (fig. 1), which is slightly above the long-term average number of earthquakes per year of 1,500–2,500. The total includes 10 magnitude 3 earthquakes, 163 magnitude 2 earthquakes, and 2,600 earthquakes with magnitudes less than 2. Four earthquakes during the year were felt, meaning that people reported some shaking. The largest event of the year was a magnitude 3.6 earthquake, which occurred beneath Yellowstone Lake on July 16 at 6:45 p.m. local time.

Of the total number of recorded earthquakes, about 65 percent occurred as part of 26 swarms, which are defined as the

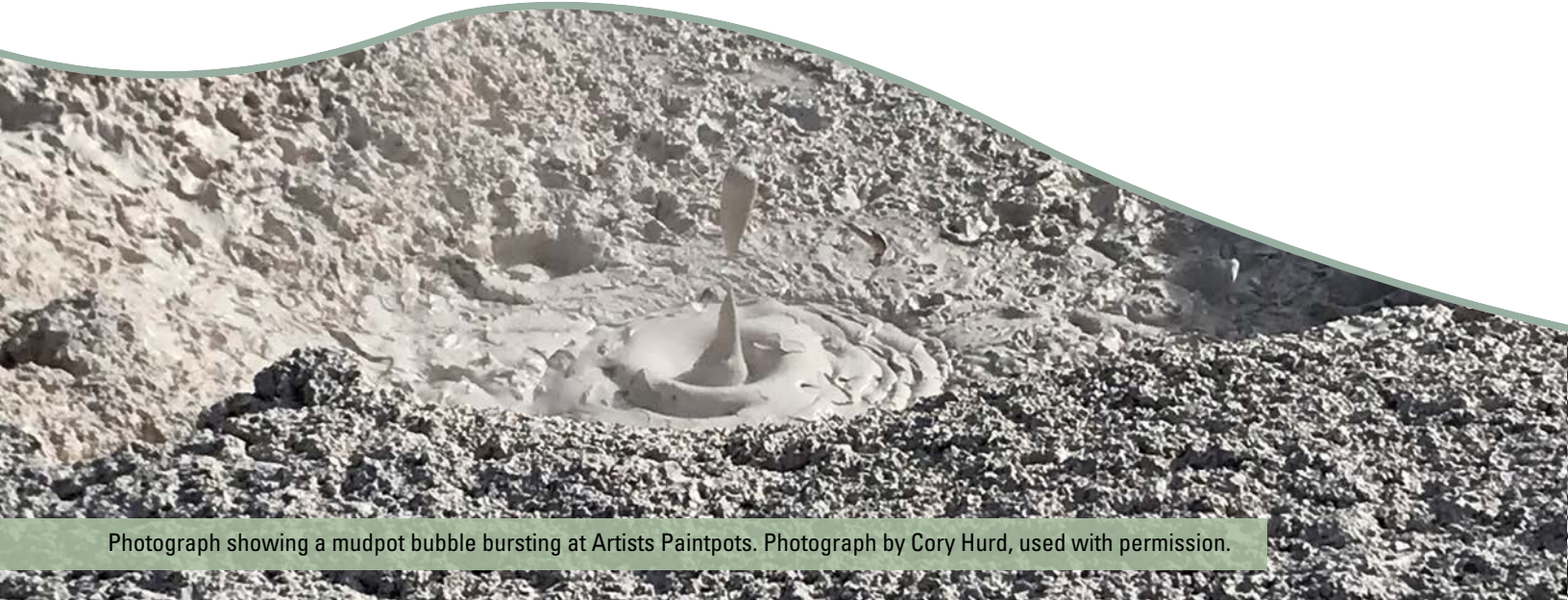
occurrence of many earthquakes in the same small area over a relatively short period of time. Swarm activity is common in the Yellowstone region and typically includes about half of all earthquakes that take place in the region. The largest swarm in 2021 was characterized by 825 events during July 15–25 beneath Yellowstone Lake. Other notable swarms during the year included 180 events located about 18.5 kilometers (11.5 miles) northeast of West Yellowstone (Montana), in the region between Hebgen Lake and Norris Geyser Basin, during June 26–July 4; 119 events located about 7.5 kilometers (4.7 miles) southeast of Madison Junction during June 21–23; and 113 events located about 9 kilometers (5.6 miles) east of Madison Junction during September 16–24.

Outside of the Yellowstone region, aftershocks from the central Idaho magnitude 6.5 tectonic earthquake on March 31, 2020, continued at a gradually decreasing rate throughout 2021. The mainshock and aftershocks are unrelated to the Yellowstone volcanic system and have not caused changes in seismic or hydrothermal activity in the national park. YVO nevertheless answered many questions from concerned citizens who feared the earthquakes were related to the volcanic system.

During the year, the University of Utah performed major maintenance work on the two main data transmission nodes for the Yellowstone Seismic Network on Mount Washburn and Sawtell Peak. Changes included upgrades to backup power systems as well as adding reliable backup telemetry links to compensate for any failure in the primary telemetry links. This work will ensure reliable transmission of seismic data throughout the year.

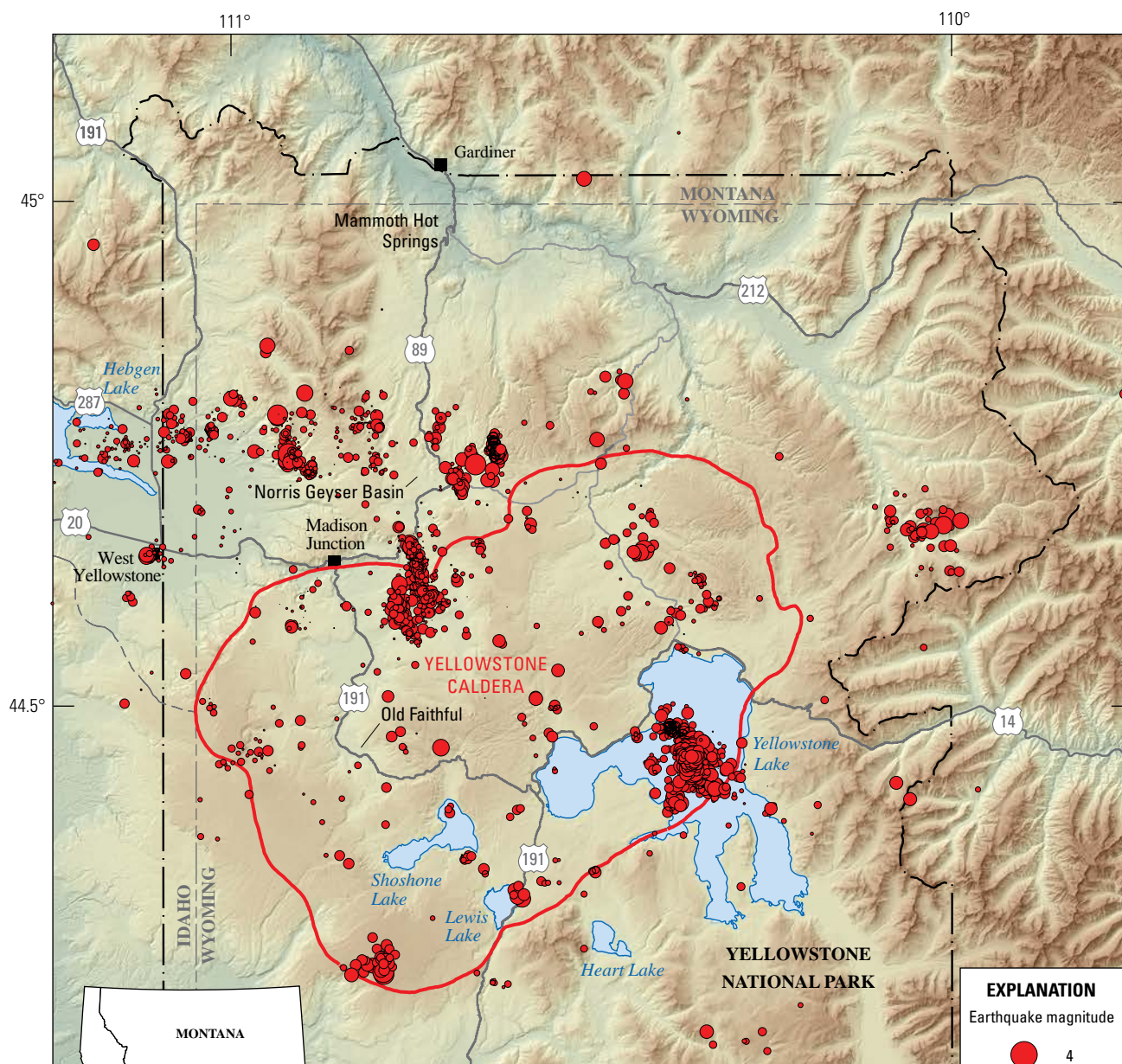
### Seismic Studies of Geyser Systems

In June of 2021, the University of Utah, in collaboration with Yellowstone National Park, deployed 140 seismometers around Steamboat Geyser, Cistern Spring, and the Norris Geyser Basin as part of a research project funded by the National Science Foundation (NSF) under Yellowstone National Park research permit YELL–2021–SCI–8058. The project was a continuation of past deployments in Norris Geyser Basin focused on Steamboat



Photograph showing a mudpot bubble bursting at Artists Paintpots. Photograph by Cory Hurd, used with permission.





**Figure 1.** Map of earthquakes (red circles) that occurred during 2021 in the Yellowstone National Park region. Circle size is scaled to the magnitude of the earthquake, where larger circles represent stronger earthquakes.

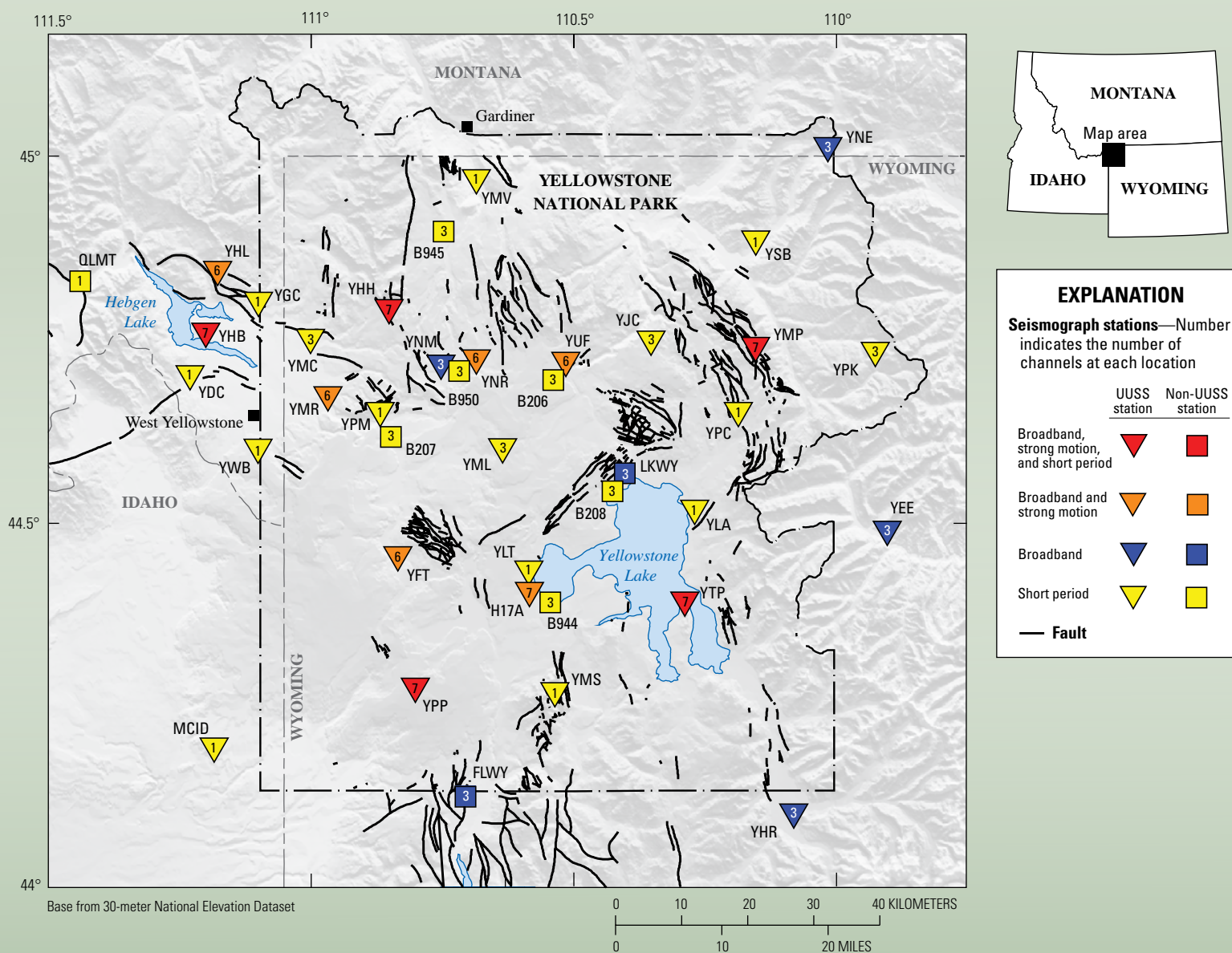


## Seismicity in Yellowstone Plateau

Seismicity in the Yellowstone Plateau is monitored by the University of Utah Seismograph Stations. The earthquake monitoring network, known as the Yellowstone Seismic Network, consists of about 46 seismometers installed in the seismically and volcanically active Yellowstone National Park and surrounding area. It is designed for the purpose of monitoring earthquake activity associated with tectonic faulting as well as volcanic and hydrothermal activity. Data are also used to study the subsurface processes of Yellowstone Caldera.

Seismic monitoring in the Yellowstone Plateau began in earnest during the early 1970s, when a seismic network was installed by the U.S. Geological Survey. This network operated until the early 1980s when it was discontinued for budgetary reasons. The network was re-established and expanded by the University of Utah in 1984 and has been in operation ever since. Over the years, the Yellowstone Seismic Network has been updated with modern digital seismic recording equipment, making it one of the most modern volcano-monitoring networks in the world.

Presently, data are transmitted from seismic stations in the Yellowstone region to the University of Utah in real-time using a sophisticated radio and satellite telemetry system. Given that Yellowstone Plateau is a high-elevation region that experiences heavy snowfall and frigid temperatures much of the year, and that many of the data transmission sites are located on tall peaks, it is a challenge to keep the data flowing during the harsh winter months. It is not uncommon for seismometers to go offline for short periods when the solar panels or antennas are covered in snow.



Map of seismometer station locations operated by the University of Utah Seismograph Stations (UUSS) and other agencies. Map view shows the Yellowstone Plateau earthquake catalog region.

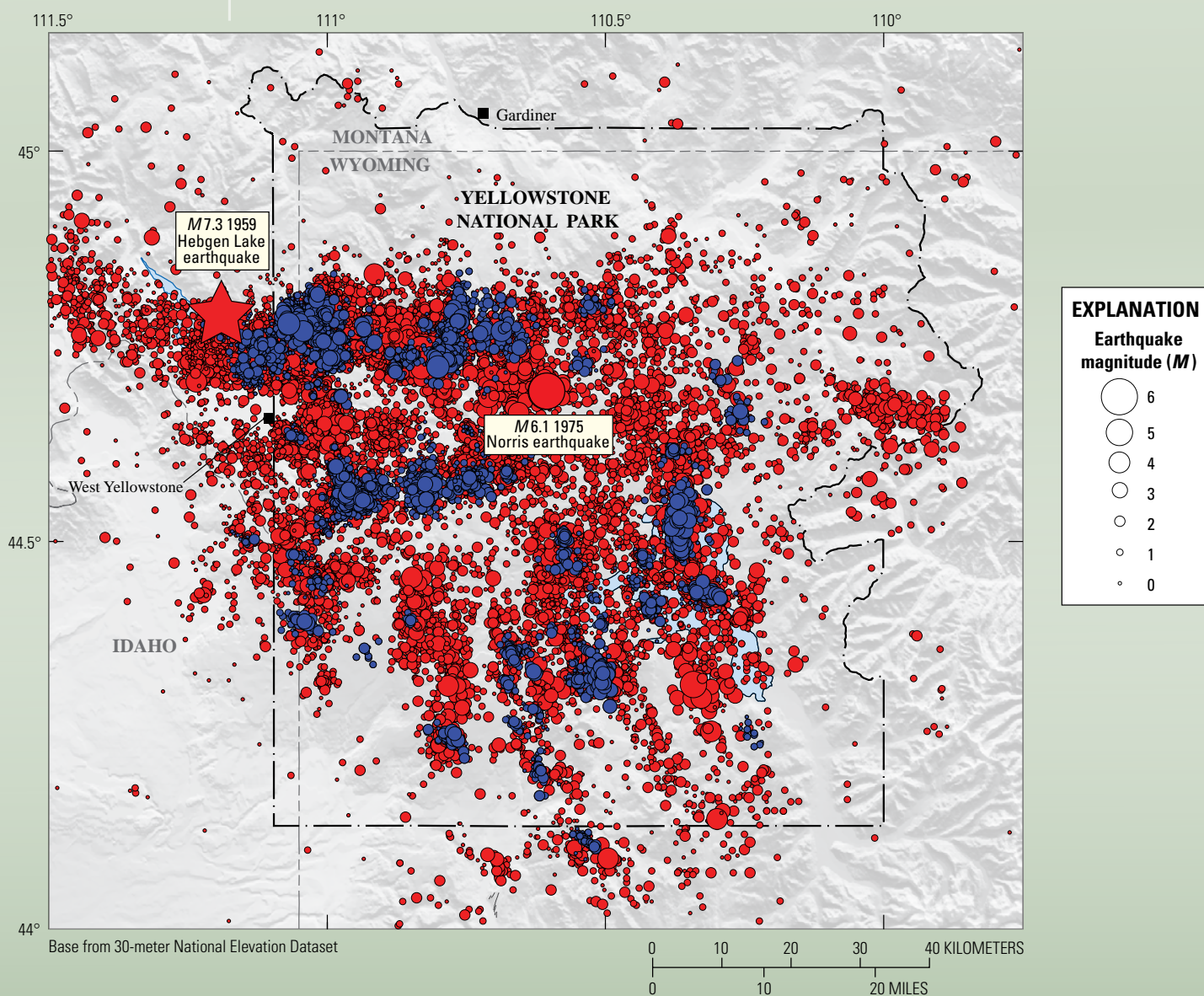


and ice. Sometimes seismometers that go offline during the winter cannot be accessed until the following spring.

Since 1973, there have been more than 50,000 earthquakes located in the Yellowstone region. More than 99 percent of those earthquakes are magnitude 2 or below and are not felt by anyone. Since 1973, there has been one magnitude 6 event—the 1975 magnitude 6.1 Norris earthquake located near Norris Geyser Basin (the largest earthquake ever recorded in Yellowstone National Park). There have also been two earthquakes in the

magnitude 5 range, 29 earthquakes in the magnitude 4 range, and 404 earthquakes in the magnitude 3 range. The largest earthquake ever recorded in the Yellowstone region was the 1959 magnitude 7.3 Hebgen Lake earthquake, which was located just west of the national park boundary and north-northwest of West Yellowstone, Montana. That earthquake was responsible for 28 deaths and had a major impact on the hydrothermal systems of nearby Yellowstone National Park, including Old Faithful Geyser.

Earthquake swarms (earthquakes that cluster in time and space) account for about 50 percent of the total seismicity in the Yellowstone region. Though they can occur anywhere in the region, they are most common in the east-west band of seismicity between Hebgen Lake and Norris Geyser Basin. Most swarms consist of short bursts of small-magnitude earthquakes, containing 10–20 events and lasting for 1–2 days, although large swarms of thousands of earthquakes lasting for months do occur on occasion (for example, in 1985–86 and in 2017).



Map of earthquakes in the Yellowstone region as located by the University of Utah Seismograph Stations from 1973–2017. Red circles represent individual earthquakes and blue circles individual earthquakes that were part of swarms. The size of the circles is scaled to the magnitude ( $M$ ) of the earthquake, where larger circles represent stronger earthquakes.



Geyser and its recent eruptive activity. The seismic array was deployed from June 10 until July 18. Because of increased eruption intervals during the summer of 2021 (see “Steamboat Geyser” section), the network only recorded one major eruption of Steamboat Geyser during the deployment. The data will be used to better image the plumbing systems of Steamboat Geyser and Cistern Spring to greater depths than before, possibly leading to an explanation of why the geyser eruptions are the tallest in the world. The broader array around Norris Geyser Basin will be used to calculate seismic velocities of the subsurface, and researchers will be able to use that information to potentially pinpoint hydrothermal feature targets for future deployments of dense seismometer arrays.

A second NSF-funded deployment of 270 seismometers occurred in the Upper Geyser Basin in November 2021, led by the University of Utah and the University of California, Berkeley, in collaboration with Yellowstone National Park. The seismic array was focused on Old Faithful Geyser, Doublet Pool, Black Sand Pool, and Grand Geyser (fig. 2). The instruments recorded continuous seismic data for approximately 1 week and then were removed. In conjunction with the seismic instrumentation, additional work included deployment of a hydrophone in the pools, collection of water samples and temperature records from Doublet and Black Sand Pools, and measurements of the gas content coming out of the hydrothermal features. The purposes of the project were to continue long-term studies of Old Faithful Geyser with a much denser array of seismometers and to learn more about Grand Geyser and Doublet and Black Sand Pools. Both Doublet and Black Sand Pools are well known for their distinctive “thumping”—an intermittent yet rhythmic process that can be heard and felt—and the 2021 data will help scientists better understand why these features thump and how these thermal pools operate. In addition, looking at temporal changes of the timing between thumping episodes and the duration of those episodes at Doublet Pool can provide information about changes that are going on beneath the Geyser Hill region over time and how those changes can be correlated to those at other nearby features, as well as to

variations in local hydrology and weather. These data, combined with results from deployments in previous years (see 2017 and 2018 YVO annual reports [YVO, 2019, 2021a]), can reveal not only what these hydrothermal features look like beneath the ground, but also how they interact with one another and are influenced by external factors, like weather.

## Geodesy

Geodesy is the scientific discipline focused on changes in the shape of Earth’s surface, called deformation. In and around Yellowstone Caldera, deformation is caused by a combination of magmatic, tectonic, and hydrothermal processes. Ground motion is measured using networks of GPS<sup>2</sup> stations, borehole tiltmeters and strainmeters, and a satellite-based remote-sensing technique called interferometric synthetic aperture radar (InSAR) (see sidebar on monitoring geodetic change on p. 10–12). Changes in Earth’s gravity field, which can indicate subsurface mass changes caused by movement of magma or groundwater, for example, also fit within the purview of geodesy. Geodetic measurements are used to develop models of the sources of deformation and gravity changes as far as several kilometers (miles) below the surface, which can provide insights into the physical processes responsible for changes measured at the surface.

## Overall Deformation in 2021

The most notable change in the deformation pattern in 2021 was resumption of uplift along the north rim of the caldera to the south of Norris Geyser Basin—an area that also experienced uplift during 1996–2004. In 2021, the amount of uplift totaled about 1 centimeter (0.4 inch). Subsidence

<sup>2</sup>In this report, we use GPS as a general and more familiar term for Global Navigation Satellite Systems (GNSS), even though GPS specifically refers to the Global Positioning System operated by the United States.

**Figure 2.** Photograph looking southwest from the boardwalk showing seismic nodes (white cylinders) deployed around Doublet Pool in Upper Geyser Basin. Old Faithful Basin Store and service station are in the background at left. Photograph by Jamie Farrell, University of Utah, November 13, 2021. Research carried out under Yellowstone Research Permit YELL-2016-SCI-8058.

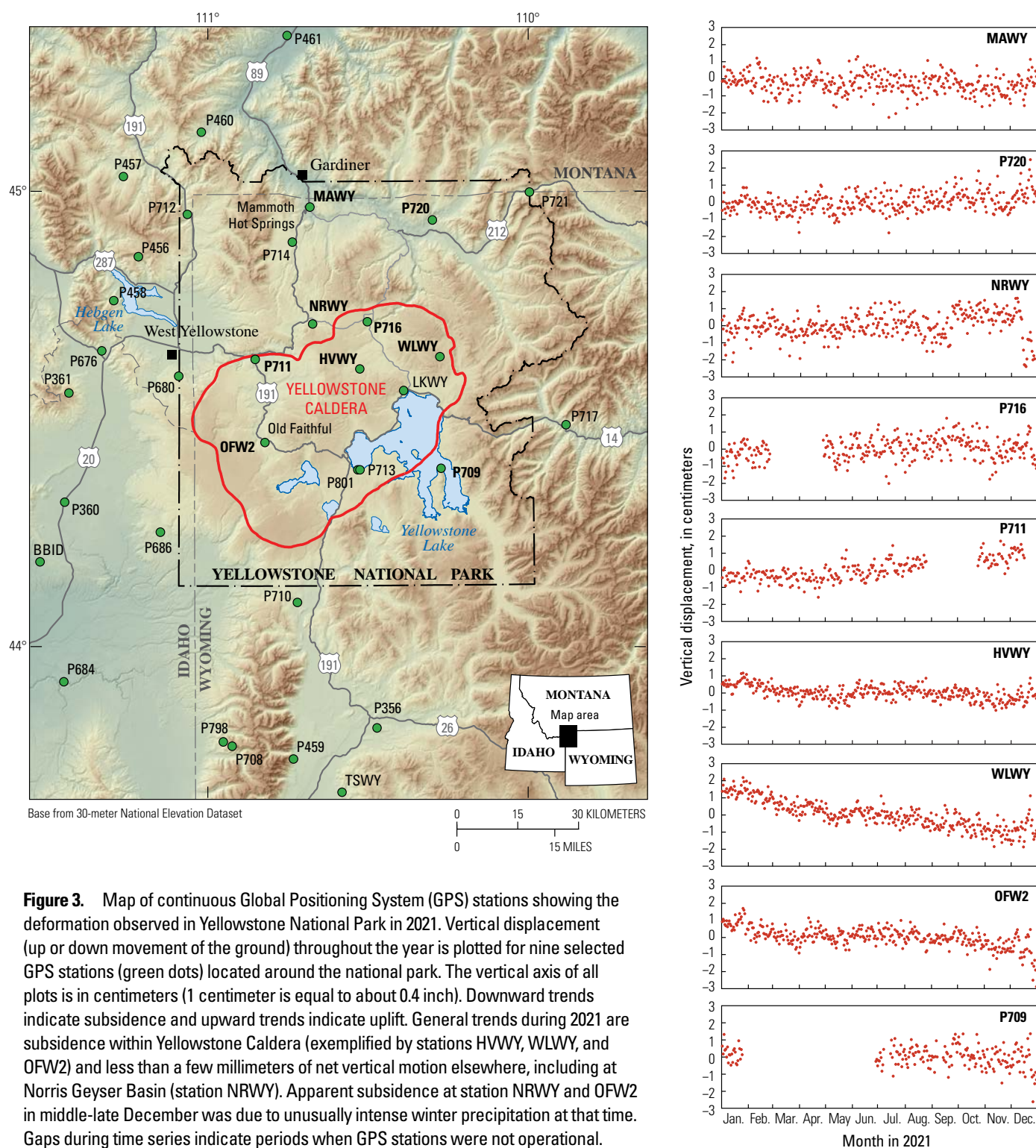




of the floor of Yellowstone Caldera occurred at a rate of 2–3 centimeters (about 1 inch) per year (fig. 3), continuing the trend that, except for a brief period of uplift in 2014–2015, has persisted since 2010. At Norris Geyser Basin, a period of rapid uplift began in late 2015 or early 2016, stalled in late 2018, and was followed by a minor amount of subsidence that ceased in 2020, with no significant changes in 2021 (fig. 3).

In 2021, there were five borehole tiltmeters and four borehole strainmeters operating within Yellowstone National

Park. These exceptionally sensitive instruments are most useful for detecting short-term changes in deformation (for example, owing to earthquakes or sudden fluid movements). Because their signals can drift over periods of weeks to months and show trends that are not related to deformation, tilt and strain measurements are less useful for determining long-term (months to years) deformation patterns. The tiltmeter and strainmeter networks detect no meaningful changes during 2021.



**Figure 3.** Map of continuous Global Positioning System (GPS) stations showing the deformation observed in Yellowstone National Park in 2021. Vertical displacement (up or down movement of the ground) throughout the year is plotted for nine selected GPS stations (green dots) located around the national park. The vertical axis of all plots is in centimeters (1 centimeter is equal to about 0.4 inch). Downward trends indicate subsidence and upward trends indicate uplift. General trends during 2021 are subsidence within Yellowstone Caldera (exemplified by stations HVWY, WLWY, and OFW2) and less than a few millimeters of net vertical motion elsewhere, including at Norris Geyser Basin (station NRWY). Apparent subsidence at station NRWY and OFW2 in middle-late December was due to unusually intense winter precipitation at that time. Gaps during time series indicate periods when GPS stations were not operational.



## Monitoring Geodetic Change in the Yellowstone Region

Subtle changes to the shape of a volcano's surface, called deformation, can be caused by the accumulation, withdrawal, or migration of magma, gas, or other fluids (typically water) beneath the ground, or by movements in Earth's crust owing to motion along faults. Typically, this deformation is very small in magnitude—a few centimeters (inches) or less—and so can only be detected and monitored using very sensitive instruments. Changes in the amount of material beneath the ground also result in variations in gravity at the surface. Combining measurements of gravity change with deformation can help scientists determine the type of fluid that is accumulating or withdrawing—for example, magma versus gas.

By measuring the pattern and style of surface deformation, it is possible to determine the location of subsurface fluid storage areas. For example, as magma or water accumulates in a reservoir below ground, the surface above will swell. The pattern of this surface inflation can be used to identify the depth of fluid accumulation, and the scale of the deformation can provide information on how much and what type of fluid is accumulating. By monitoring changes in deformation over time, it is possible to assess how magma, water, and gas are moving in the subsurface. The technique is an important tool for forecasting potential future volcanic eruptions. In the days, months, and years before a volcanic eruption, many volcanoes inflate as magma accumulates underground. Yellowstone Caldera presents a complicated situation because deformation may be

caused by magma, water, or gas, as well as non-volcanic processes such as fault or landslide motion.

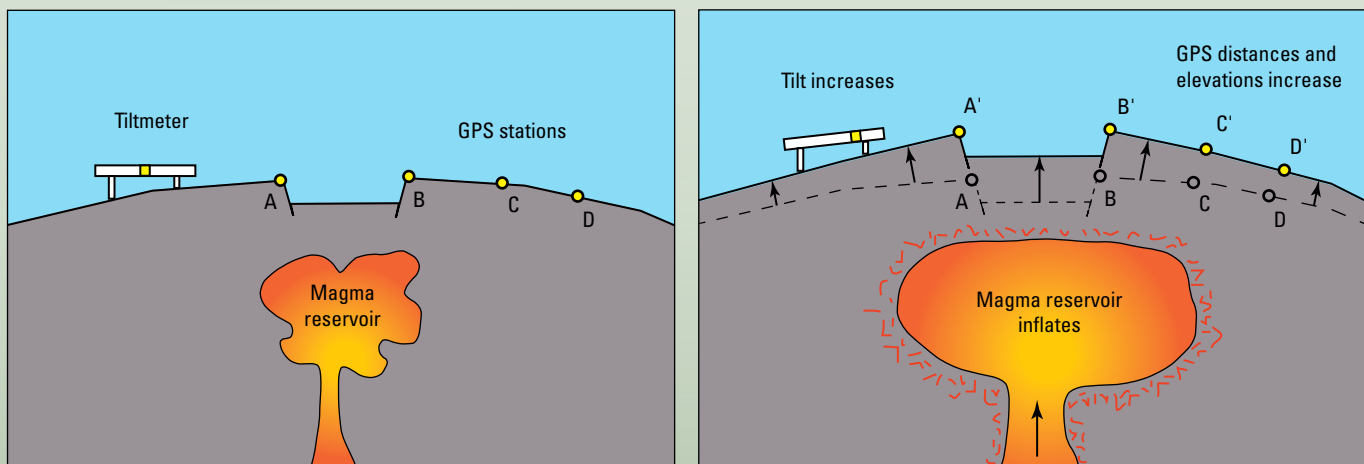
A variety of techniques are used to monitor ground deformation in the Yellowstone region. UNAVCO, a non-profit, university-governed consortium, operates the Geodetic Facility for the Advancement of Geoscience (GAGE), which includes the Network of the Americas, a hemispherical-scale geodetic network composed of geodetic-grade Global Positioning System (GPS) instrumentation as well as high-precision borehole tensor strainmeters and tiltmeters, all of which are present in Yellowstone National Park. Borehole strainmeters and tiltmeters are designed to detect very small changes in deformation style especially over short time intervals (even down to minutes), but they tend to drift over days to weeks and so cannot track long-term ground deformation. This is why GPS, the backbone of the Yellowstone Volcano Observatory deformation monitoring network, is so important.

There are 15 continuously recording GPS stations within Yellowstone National Park and many more in the surrounding region. Measurements from these sites are used to precisely record the horizontal and vertical positions of fixed points at the surface. Variation in the positions over time, relative to the rest of the North American continent, gives an indication of how the ground in the Yellowstone region deforms owing to local processes, such as subsurface fluid accumulation and withdrawal or faulting caused by earthquakes. Data from continuous GPS stations in the Yellowstone

region are transmitted via radio and satellite links to UNAVCO's archives, where they are made publicly available at <https://www.unavco.org/data/dai>.

Semipermanent GPS sites are temporary stations that are deployed in the late spring and collected in the early fall. Measurements from these portable sensors significantly add to the number of instruments measuring deformation in the Yellowstone region and help track year-to-year changes. Compared to continuous GPS, semipermanent GPS stations are less expensive and less intrusive on the landscape, and they are portable enough to be deployed in areas that might be off limits to a continuous GPS installation. Disadvantages of semipermanent GPS compared to continuous GPS are that semipermanent GPS measurements are intermittent whereas continuous GPS measurements are collected year-round, and semipermanent GPS data are not telemetered, so they are available only after the stations have been retrieved. Used together, however, the two approaches complement one another by providing precise ground deformation measurements from more than 30 sites in Yellowstone National Park.

YVO scientists also use satellite measurements, called interferometric synthetic aperture radar (InSAR), to take a broad snapshot of deformation. Two radar images of the same area that were collected at different times from similar vantage points in space are compared against each other. Any movement of the ground surface toward or away from the satellite is measured and portrayed as a



Schematic cartoon showing how the ground changes shape as magma accumulates beneath the surface. GPS, Global Positioning System.

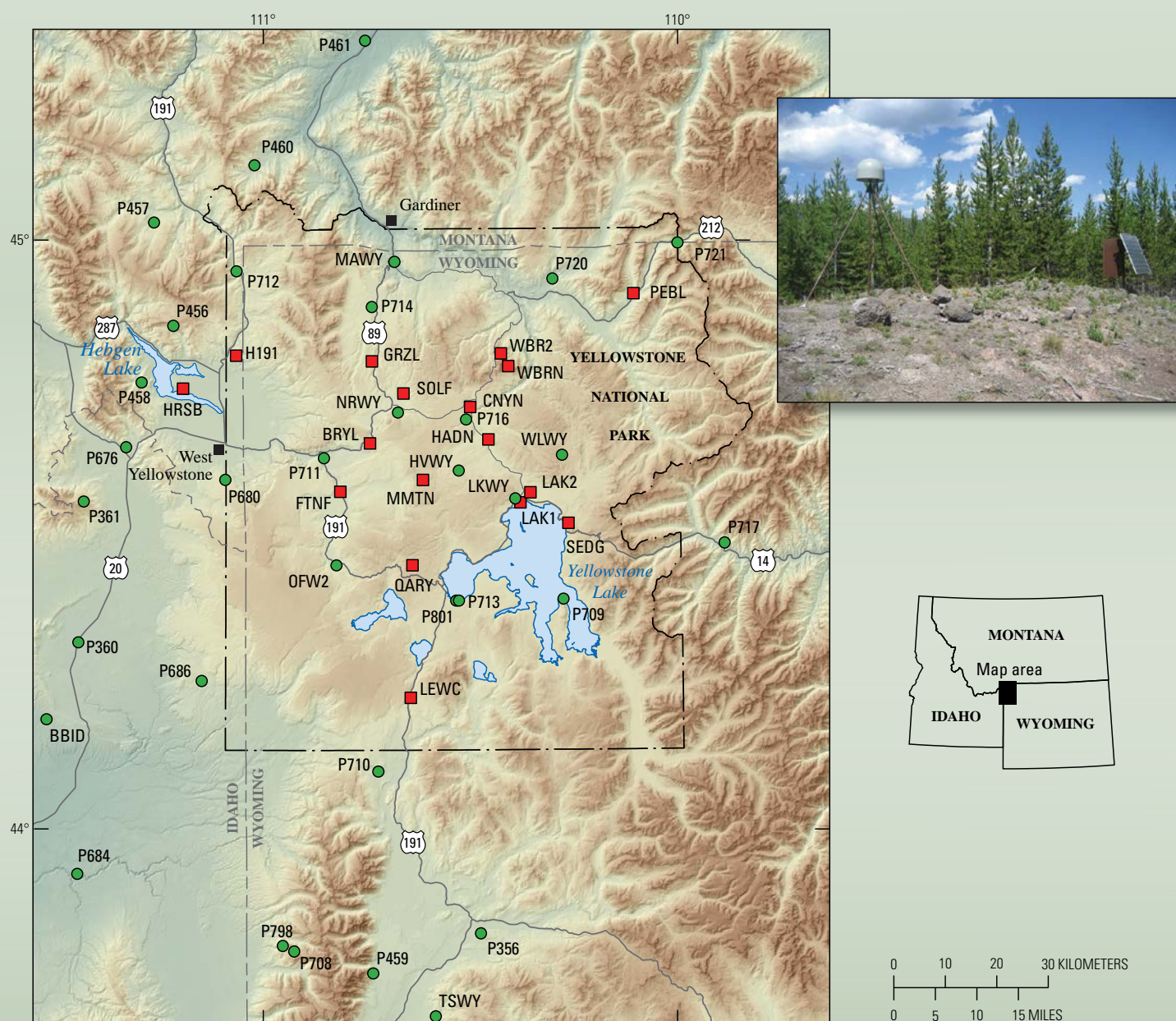


“picture”—not of the surface itself but of how much the surface moved during the time between images. Unlike visible or infrared light, radar waves penetrate most weather clouds and are equally effective in darkness; using InSAR, it is possible to track ground deformation even in bad weather and at night. Although it is less precise than GPS, InSAR has the advantages of showing the entire pattern of surface deformation as a spatially continuous image, and the technique does not require access to, or installations

in, the study area. Disadvantages are that current InSAR satellites collect images several days apart (whereas GPS measurements are continuous), InSAR only shows deformation in one direction (line-of-sight of the satellite) compared to the three-dimensional deformation measured by GPS, and InSAR measurements are not usable during winter months in the Yellowstone region because most of the surface is covered with snow.

Measurements of changes in Earth’s gravity field are another means to study

processes that occur underground, hidden from sight. For example, gravity will increase slightly if more magma accumulates in a shallow reservoir, or if porous rock fills with groundwater. By combining gravity measurements (which can record changes in subsurface mass) with deformation (which can indicate changes in subsurface volume), it is possible to calculate the density of the fluids that are driving the changes seen at the surface. High-density fluids are likely to be magma, whereas low-density fluids may be water or gas.

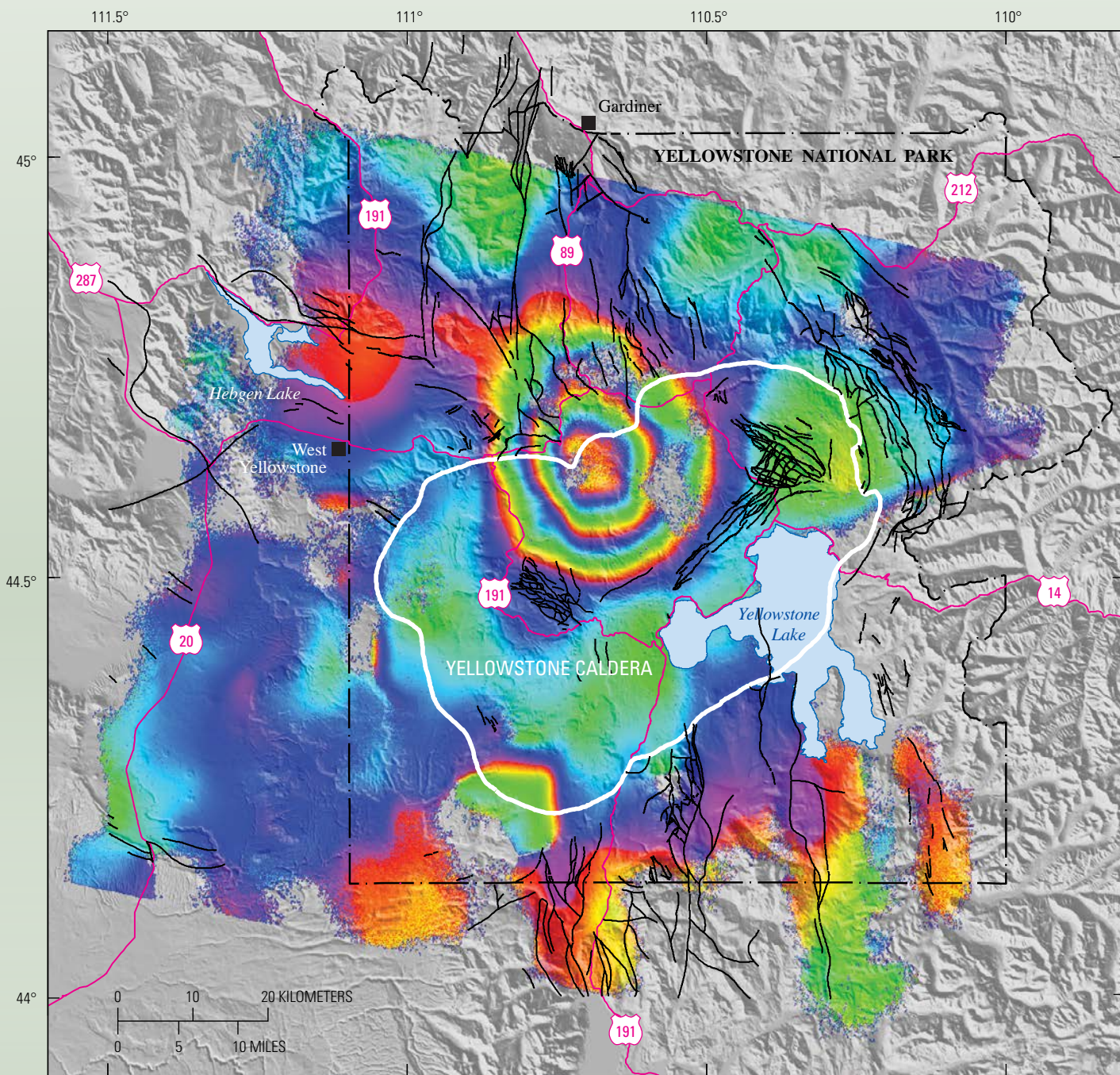


Base from 30-meter National Elevation Dataset

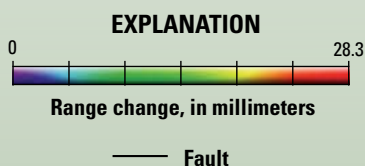
Map showing locations of continuous (green dots) and semipermanent (red squares) Global Positioning System (GPS) sites in the Yellowstone region. Photograph shows continuous GPS station P711 in Yellowstone National Park.



## Monitoring Geodetic Change in the Yellowstone Region



Base from 30-meter National Elevation Dataset



Map of past ground deformation in the Yellowstone region. This image was created using data from satellite passes in 1996 and 2000. The image shows 125 millimeters (about 5 inches) of uplift centered near the north rim of Yellowstone Caldera, about 10 kilometers (6.2 miles) south of Norris Junction. Each full cycle of color (from red through green to purple) represents about 28 millimeters (1 inch) of surface movement toward or away from the satellite (mostly uplift or subsidence). Here, the bullseye centered along the north caldera rim near Norris Geyser Basin shows an area of uplift approximately 35×40 kilometers (22×25 miles) in size. Modified from U.S. Geological Survey Professional Paper 1788 (Dzurisin and others, 2012).



## Continuous GPS Results

Throughout 2021, surface deformation measured by 15 continuous GPS stations in Yellowstone National Park mostly followed trends established during previous years. Stations inside Yellowstone Caldera subsided at rates of 2–3 centimeters (about 1 inch) per year, following patterns that have been ongoing since late 2015 or early 2016 (see fig. 3, especially stations HVWY, WLWY, and OFW2). The subsidence appears to have stalled and may have even reversed at some stations during the summer months (May–September), but subsidence resumed after that time. This seasonal variation is observed during most summers and is probably related to groundwater recharge or other environmental factors, not to the magmatic or hydrothermal systems. Regardless, the change was too small to affect the overall caldera deformation pattern observed since 2015.

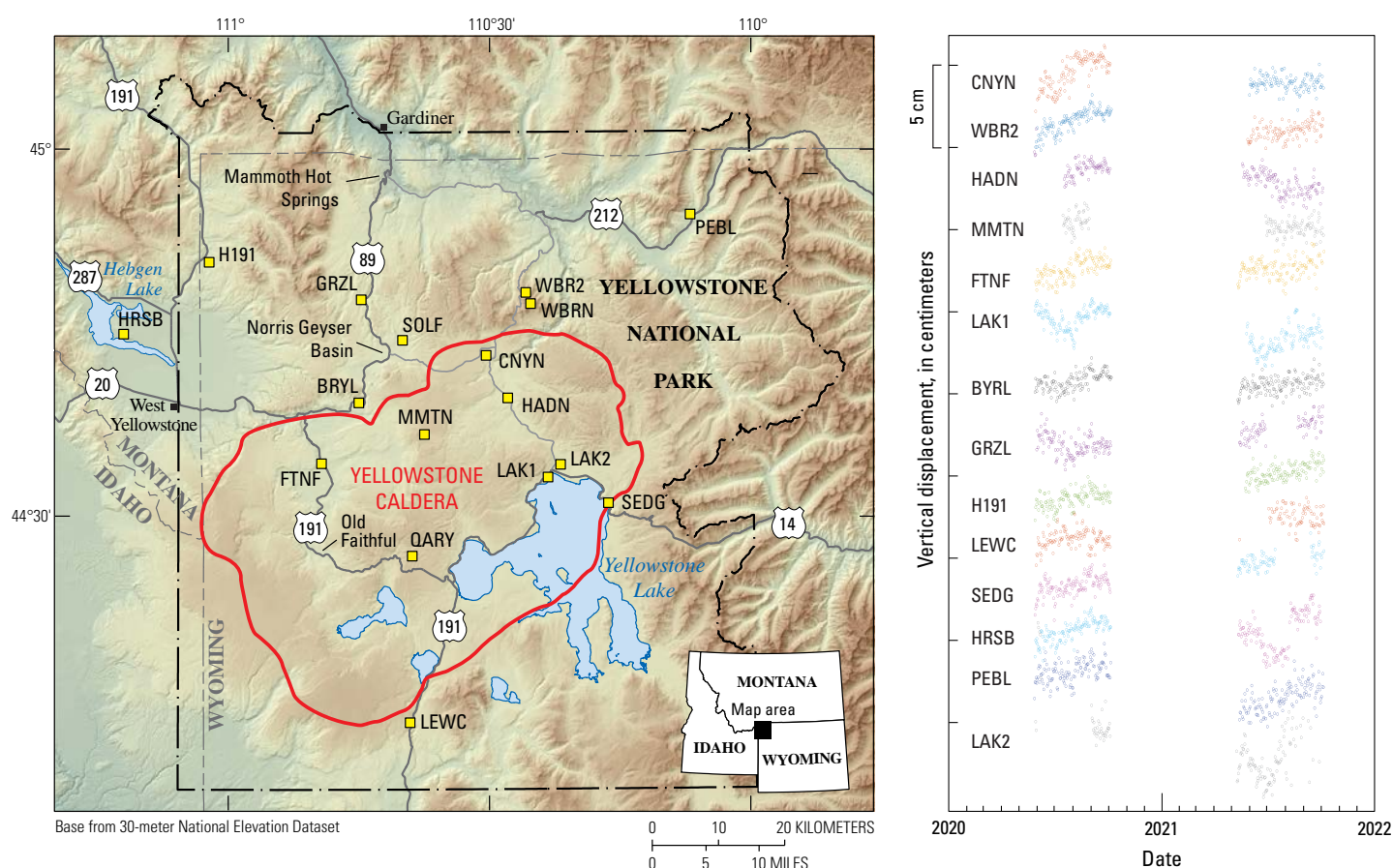
At Norris Geyser Basin, 2021 was uneventful with no ground deformation above the detection threshold of about 5 millimeters (less than 0.2 inch). Uplift that began in late 2015 or early 2016 paused in late 2018 (see 2018 YVO annual report [YVO, 2021a]) and gave way to slow subsidence in September 2019, which stopped in 2020. A small amount of uplift was apparent during the summer months, but this probably reflected seasonal groundwater recharge, as has been observed at sites within the caldera. Station P711, southwest of Norris Geyser Basin, also showed some uplift,

which may similarly be seasonal. This station, however, is close to a historical source of uplift along the north rim of the caldera that appears to have reactivated in 2021 (see “InSAR” section, below). The coming year will be important for understanding the sensitivity of this GPS station to the uplift anomaly.

Station coordinates and daily time-series plots for the Yellowstone region continuous GPS stations are available at <https://earthquake.usgs.gov/monitoring/gps/YellowstoneContin>.

## Semipermanent GPS Results

As in the previous year, in 2021 the semipermanent GPS network in the Yellowstone region comprised 16 stations in the park and one in the adjacent Hebgen Lake Ranger District of Gallatin National Forest (fig. 4). Fifteen of the 17 stations were deployed in middle May; a station high on Mount Washburn and a backcountry station on Mary Mountain, the latter established in 2020, were deployed in late June. When they were visited in late June, all stations deployed in May were recording data except station QARY, which had been disturbed by wildlife. All 17 stations were undisturbed and recording data when they were retrieved in early October. These semipermanent deployments are designed to complement the permanent GPS network and to take advantage of generally benign summertime conditions to collect



**Figure 4.** Map of semipermanent Global Positioning System (GPS) stations showing changes observed in Yellowstone National Park from 2020 to 2021. Vertical displacement (up or down movement of the ground) is plotted for 14 selected semipermanent GPS stations (yellow squares on map) located around or just outside the park. The distance between tick marks on the vertical axis is 5 centimeters (cm) (about 2 inches). Downward trends indicate subsidence and upward trends indicate uplift.



data while avoiding harsh Rocky Mountain winters. For more information on the semipermanent GPS technique, see the sidebar on monitoring geodetic change (p. 10–12).

Ten of the 17 semipermanent GPS stations recorded data successfully for the entire time they were deployed in 2021. Equipment failures or animal disturbances, some of which were corrected during a visit in late June, resulted in partial data loss at seven stations. Overall, the semipermanent GPS network recorded 2,251 data days out of a potential 2,374 data days, for a success rate of about 95 percent—about the same as 2020.

Both semipermanent GPS and continuous GPS stations record not only ground deformation caused by volcanic and tectonic processes, but also unrelated short-term signals. These short-term signals include seasonal effects, like changes in lake and groundwater levels that cause variable loading of the surface, as well as noise that occurs when a GPS antenna is covered with snow or ice, which is especially common near the start or end of an annual deployment. Such signals are easier to identify on records from continuous GPS stations than from semipermanent GPS stations, which are deployed for only part of the year. For this reason, unless the deformation rate is unusually high, data from semipermanent GPS stations are best compared from year to year, ignoring trends during any one year.

During 2020–2021, most of the semipermanent GPS stations recorded only seasonal effects or weather-related noise, with little net change (fig. 4). There was a hint of net subsidence at station HADN in the northeastern part of the caldera, consistent with InSAR observations (see next section) and with continuous GPS results (see previous section), but the change was not as strongly manifested at station MMTN, another caldera-floor semipermanent GPS site. Stations GRZL and FTFN showed small amounts of net uplift from 2020 to 2021 that may be consistent with uplift centered on the north rim of the caldera, but the change was not definitive, considering that comparably sized changes that occurred elsewhere in the network are likely to be seasonal, weather related, or other spurious effects (for example, apparent uplift at stations H191, LEWC, and SEDG). In short, both caldera-floor subsidence and slight uplift to the south of Norris Geyser Basin that are revealed by InSAR were too small to be confidently detected by semipermanent GPS during 2020–2021. As in past years, two sites near the shore of Yellowstone Lake (stations LAK1 and LAK2) recorded seasonal effects caused by changes in surface loading by lake water—subsidence when snowmelt caused lake level to rise in early summer and uplift when the level receded (see 2017 YVO annual report [YVO, 2019]).

Station coordinates and daily time series plots for the semipermanent GPS stations in the Yellowstone region are available at [https://earthquake.usgs.gov/monitoring/gps/Yellowstone\\_SPGPS](https://earthquake.usgs.gov/monitoring/gps/Yellowstone_SPGPS).

## InSAR

Satellite InSAR uses measurements from radar satellites to map ground deformation by comparing satellite-to-ground distances at different times. Resulting images are called interferograms, and they show how much the surface moved during the time between satellite observations. For more

information about the InSAR technique, see the sidebar on monitoring geodetic change (p. 10–12).

A radar interferogram that spans the period from September 22, 2020, to September 17, 2021, shows about 3.3 centimeters (1.3 inches) of subsidence of the caldera, maximized on the east side at the Sour Creek resurgent dome (fig. 5). In the same interferogram, about 1.0 centimeter (0.4 inch) of uplift is apparent along the north rim of the caldera to the south of Norris Geyser Basin—a pattern similar to that seen during the onset of an uplift episode that began in 1995–1996 and lasted until 2004 (Wicks and others, 2020). Through the end of 2021, the uplift was too small to be obvious in continuous and semipermanent GPS measurements (see previous sections). The coming year will be critical for understanding the development of this interesting feature. The previous episode of uplift in this area lasted for about 8 years and accumulated 12 centimeters (4.7 inches) of uplift at rates of about 1.5 centimeters (0.6 inch) per year.

## Geochemistry

Geochemical studies of Yellowstone National Park's diverse and dynamic thermal features are aimed at better understanding the interface between its hydrothermal and magmatic systems, with the ultimate goal of investigating processes that are hidden from direct observation (see sidebar on geochemical monitoring on p. 16). Thermal features provide a window into Yellowstone National Park's subsurface characteristics, and geochemistry is a powerful tool for illuminating those depths, as well as detecting gases possibly emanating from subsurface magma.

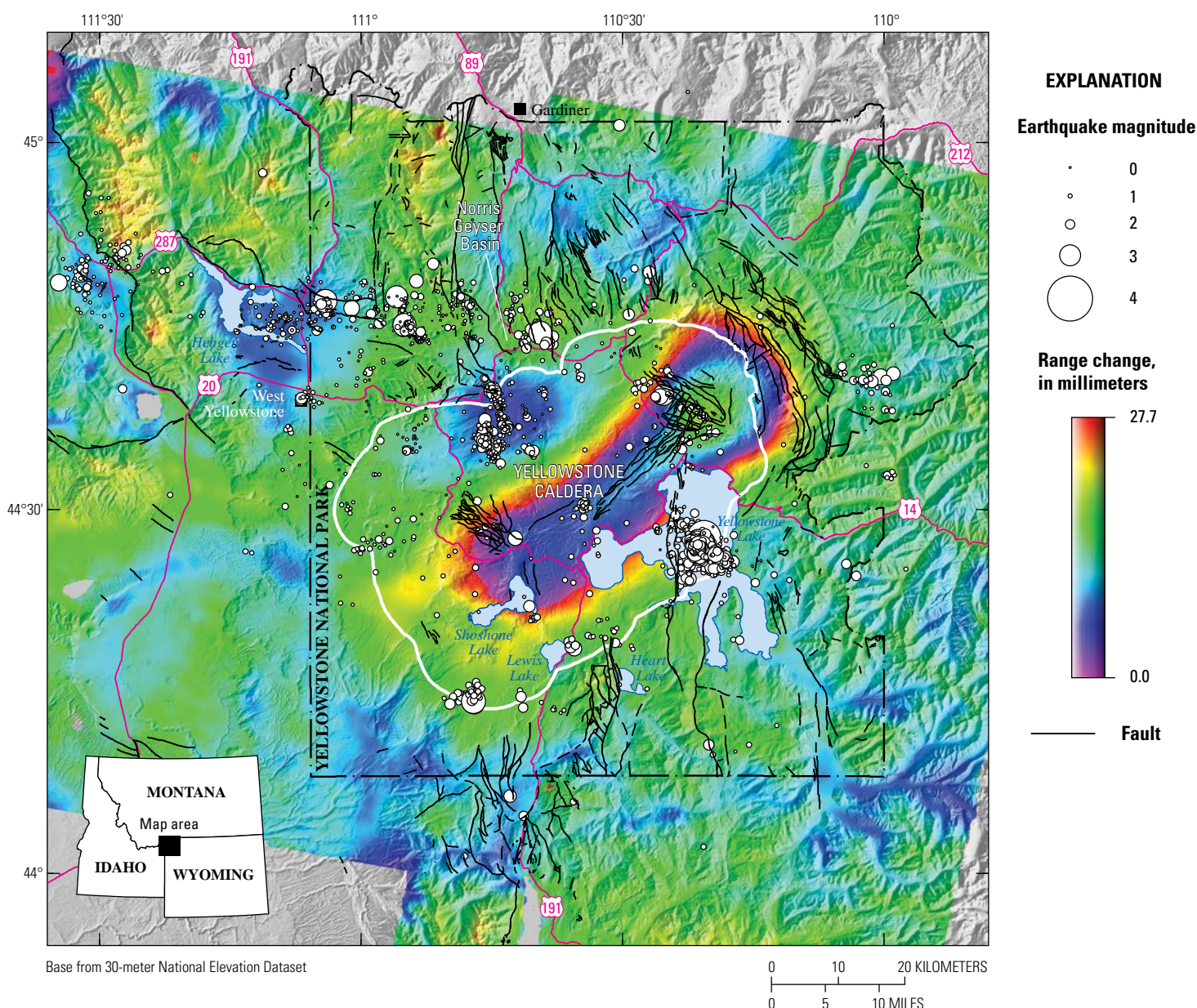
### Summary of Geochemistry Activities in 2021

In 2021, YVO scientists continued with gas emission measurements and collected water samples in various areas for laboratory analysis. A multicomponent gas analyzer system (multi-GAS) was installed in the Mud Volcano area in July to collect continuous measurements of water vapor ( $H_2O$ ), carbon dioxide ( $CO_2$ ), hydrogen sulfide ( $H_2S$ ), and sulfur dioxide ( $SO_2$ )—the first such year-round system ever installed in Yellowstone National Park! Water samples were collected from Upper Geyser Basin, Hillside Springs, Calcite Springs, Potts Hot Spring Basin, Crater Hills, Vermilion Springs, Fountain Paint Pot, and Norris Geyser Basin to better understand the geological, geochemical, and biological processes that influence water chemistry.

## Gas Emissions

A new study of gas emissions from the Obsidian Pool thermal area of Mud Volcano commenced in July 2021. The purpose of this ongoing study is to characterize, for the first time, high-resolution, real-time variations in the chemical compositions (and eventually the fluxes) of gases emitted from hydrothermal features in the Obsidian Pool thermal area. Gases emitted from the Mud Volcano area have the highest magmatic contributions in the Yellowstone region,





**Figure 5.** Interferogram created from data collected on September 22, 2020, and September 17, 2021, over the Yellowstone region by the Sentinel-1 satellite system. Colored fringes indicate a change in distance (called range change) between the satellite and ground surface that is caused by surface deformation. In this interferogram, the fringes indicate subsidence (an increase in the range between the ground and the satellite) of about 3.3 centimeters (about 1.3 inches) in the eastern part of Yellowstone Caldera, and a smaller amount of uplift (1.0 centimeter, or 0.4 inch) along the north part of the caldera to the south of Norris Geyser Basin during the period spanned by the images. White circles show earthquakes that occurred during the time spanned by the interferogram. Circle size scales with magnitude, with the largest about magnitude 3.6.

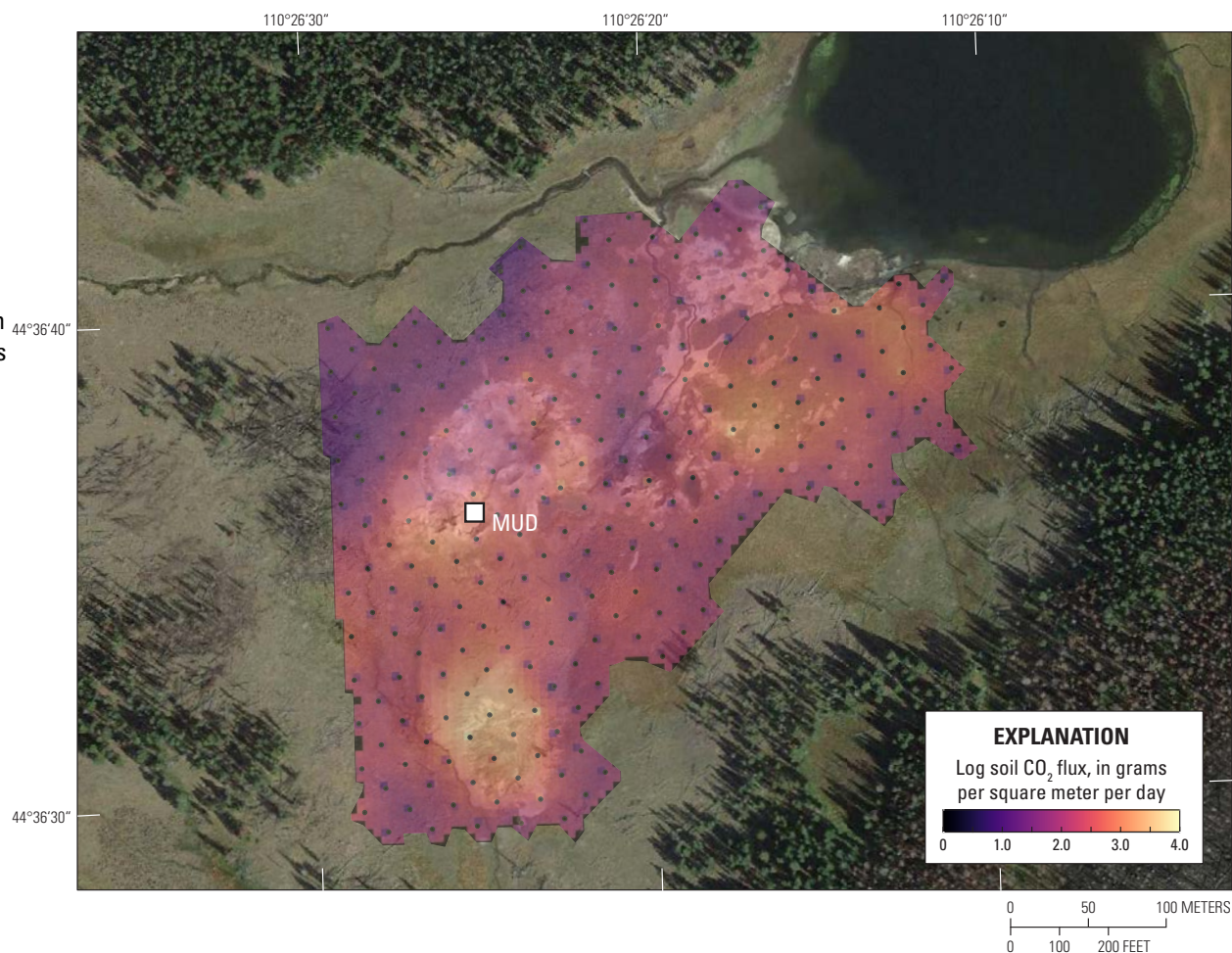
and monitoring in the area may thus provide an important comparison to prior studies at Norris Geyser Basin and Solfatara Plateau thermal area (Lewicki and others, 2017; YVO, 2019, 2021a,b,c).

A multi-GAS station was installed on July 16, 2021, adjacent to several thermal pools and what are referred to as “frying pan springs” in the Obsidian Pool thermal area (station MUD in fig. 6). The multi-GAS makes high frequency (1 hertz)  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , and  $\text{SO}_2$  measurements of gas plumes emitted from hydrothermal features, along with ancillary

meteorological parameters and ground temperatures. Whereas prior multi-GAS deployments at Norris Geyser Basin and Solfatara Plateau thermal area were limited to the summer months, major upgrades to the current system, including satellite telemetry, an improved solar power system, and an innovative lightweight equipment enclosure now permit year-round, real-time gas monitoring. The real-time measurements from multi-GAS station MUD are available on the YVO monitoring page at <https://www.usgs.gov/volcanoes/yellowstone>.



**Figure 6.** Map of log soil  $\text{CO}_2$  flux at the Obsidian Pool thermal area in Yellowstone National Park, simulated based on measurements made at the black dots. White square shows the location of the multicomponent gas analyzer system (multi-GAS) station MUD.



## SIDEBAR

### Geochemical Monitoring in Yellowstone National Park



National Park Service scientists collect water samples from the Firehole River in Yellowstone National Park. U.S. Geological Survey photograph by Jim Ball, 2014.

Deep beneath the surface, gases are dissolved in magma, but as magma rises toward the surface the pressure decreases and gases separate from the liquid to form bubbles. Because gas is less dense than magma, the bubbles can rise more quickly and be detected at the surface of the Earth.

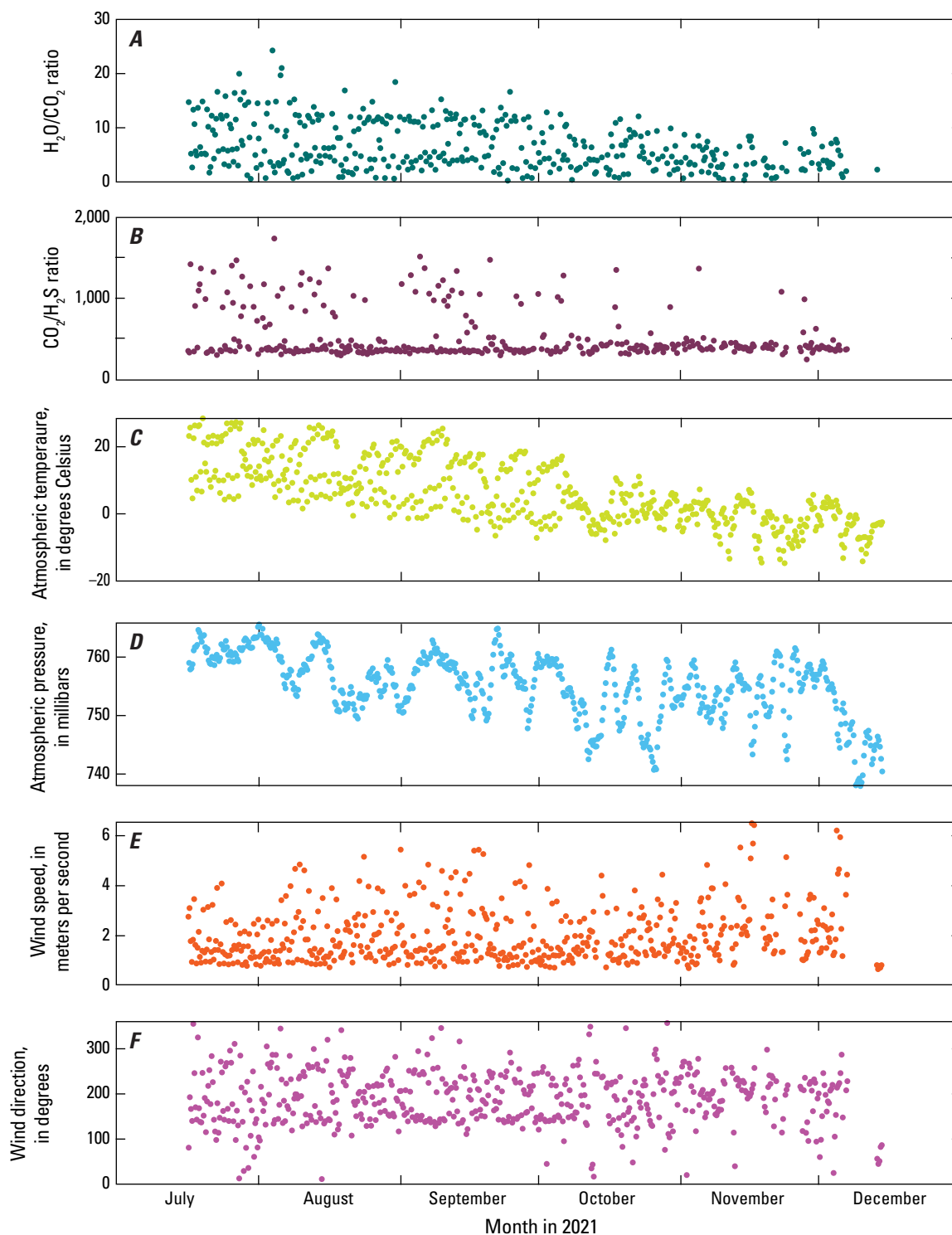
Similarly, water can also transport material up to the surface where it can be studied by scientists. Groundwater circulates deep within the Earth's crust in volcanic regions, where it can be heated by magma to more than 200 °C (around 400 °F). This heating causes water to rise along fractures, bringing dissolved chemical components up toward the surface. By studying the chemical makeup of this thermal water, scientists can gain a better picture of the conditions deep within a volcano.

In Yellowstone Caldera, volcanic gas emissions are usually sampled by hand directly from fumaroles (gas vents), although some temporary automated measurements of certain types of gases are also possible. Likewise, measurements of water chemistry are typically made by collecting samples and analyzing the chemical makeup of the water in the laboratory.



Preliminary results show that 30-minute average  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and  $\text{H}_2\text{S}$  concentrations (from samples collected every second) ranged from 2.4 to 21.9 parts per thousand, 496 to 1,113 parts per million by volume, and <0.1 to 1.8 parts per million by volume, respectively.  $\text{SO}_2$  was not detected. Time series of 30-minute average  $\text{H}_2\text{O}/\text{CO}_2$  and  $\text{CO}_2/\text{H}_2\text{S}$  ratios and meteorological parameters are shown in figure 7. Ratios of  $\text{H}_2\text{O}/\text{CO}_2$  ranged from less than 1 to 25, showed large diurnal

variations, and declined, on average, from summer to late fall (fig. 7A). These ratios correlated with atmospheric temperature (fig. 7C; correlation coefficient is 0.78), indicating that atmospheric temperature-driven condensation and evaporation of  $\text{H}_2\text{O}$  exerts a strong control on measured  $\text{H}_2\text{O}/\text{CO}_2$  ratios. Average  $\text{CO}_2/\text{H}_2\text{S}$  ratios ranged from 242 to 1,739 and, except for wind speed and direction, were poorly correlated with meteorological parameters.



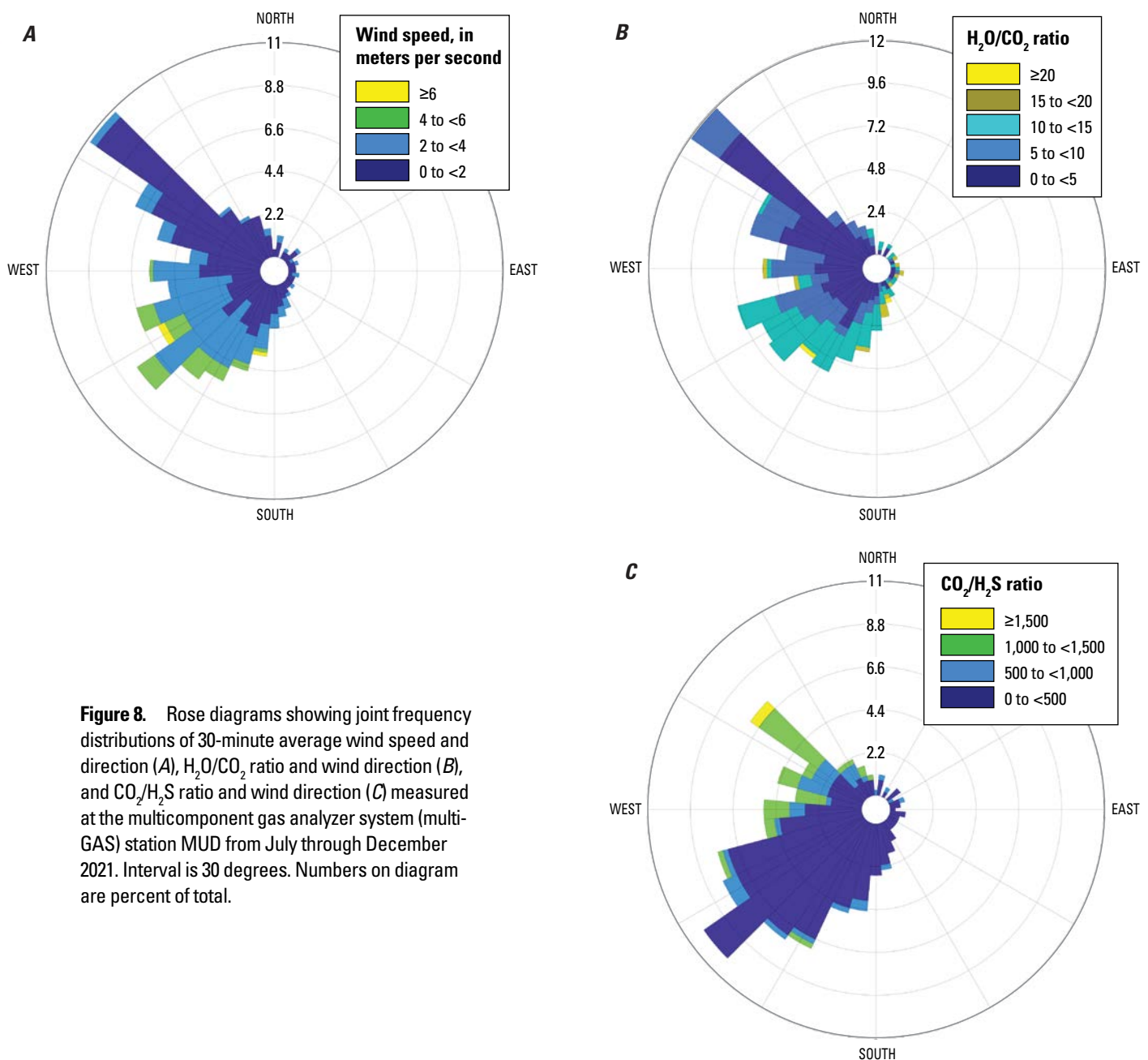
**Figure 7.** Time-series plots of 30-minute average  $\text{H}_2\text{O}/\text{CO}_2$  ratio (A),  $\text{CO}_2/\text{H}_2\text{S}$  ratio (B), atmospheric temperature (C), atmospheric pressure (D), wind speed (E), and wind direction (F) measured at the multicomponent gas analyzer system (multi-GAS) station MUD during 2021.



Winds at the Obsidian Pool thermal area site ranged dominantly from the northwest to the southwest, with relatively high wind speeds observed from the southwest (fig. 8A). Elevated  $\text{H}_2\text{O}/\text{CO}_2$  ratios tended to occur when winds were from the south to west, whereas lower ratios were typically measured when winds were from the northwest (fig. 8B). These patterns are probably related to measurement of different gas plumes from chemically diverse hydrothermal features with changing wind direction, as well as the aforementioned atmospheric effects on  $\text{H}_2\text{O}$  condensation and evaporation. Relatively high and low  $\text{CO}_2/\text{H}_2\text{S}$  ratios were typically observed when winds were from the northwest and southwest, respectively (fig. 8C). Although further analysis is required to confirm these preliminary hypotheses, patterns in  $\text{CO}_2/\text{H}_2\text{S}$  ratios likely reflect the measurement of

distinct source-vent gas compositions with changing wind directions at station MUD.

To complement continuous gas monitoring by multi-GAS, discrete gas samples were collected for laboratory analysis and a survey of soil  $\text{CO}_2$  flux was performed at the Obsidian Pool thermal area. Consistent with prior work at Mud Volcano (for instance, by Lowenstern and others, 2015), the chemical and isotopic compositions of gas samples support a large magmatic gas contribution. A map of soil  $\text{CO}_2$  flux was created from 261 measurements across the approximately 25-acre area, and the  $\text{CO}_2$  emission rate was estimated to be 27 metric tons per day (fig. 6). This emission rate is higher than the soil  $\text{CO}_2$  flux measured near Norris Geyser Basin, where results ranged from 2.4 to 9.8 metric tons per day between 2016 and 2019 (YVO, 2021b).



**Figure 8.** Rose diagrams showing joint frequency distributions of 30-minute average wind speed and direction (A),  $\text{H}_2\text{O}/\text{CO}_2$  ratio and wind direction (B), and  $\text{CO}_2/\text{H}_2\text{S}$  ratio and wind direction (C) measured at the multicomponent gas analyzer system (multi-GAS) station MUD from July through December 2021. Interval is 30 degrees. Numbers on diagram are percent of total.



## Water Sampling

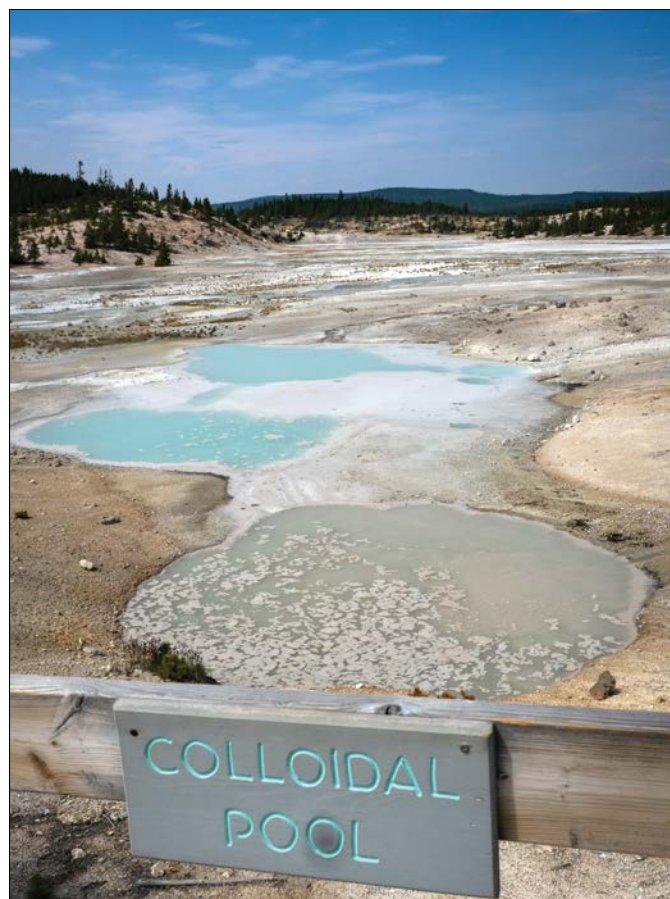
In the summer of 2021, scientists from the USGS and Yellowstone National Park sampled thermal waters at Upper Geyser Basin, Hillside Springs, Calcite Springs, Potts Hot Spring Basin, Crater Hills, Vermilion Springs, Fountain Paint Pot, and Norris Geyser Basin. At each sample site, a variety of field measurements were collected (pH, specific conductance, temperature, and  $\text{H}_2\text{S}$  content) and water samples were taken for the determination of major cations, anions, trace metals, reduction-oxidation species (iron, arsenic, and mercury), rare earth elements, water isotopes, and tritium.

The purpose of collecting water samples from each thermal area varied. Some samples were collected to monitor the chemistry of important features, such as Old Faithful Geyser in Upper Geyser Basin and Sulphur Spring in Crater Hills, whereas other sampling was done to investigate specific features or problems. Samples collected from Potts Hot Spring Basin and Fountain Paint Pot will provide supplemental chemical information for potential new sites of continuous temperature monitoring used in studies of heat flux. The seasonal effects on thermal water chemistry are being investigated at Hillside Springs, where 2 years of data have now been collected. The Hillside Springs thermal area is located on the side of a hill to the west of the Firehole River near Biscuit Basin, and the spring water is thought to be a mixture of deep thermal water and shallower groundwater—a perfect site to investigate the seasonal effects of snowmelt on the shallow hydrothermal system. The speciation and transformation of mercury and arsenic are the focus of samples collected from Calcite Springs—a unique site that discharges oil from rocks deep below the surface. Norris Geyser Basin is one of the most dynamic and hottest areas in Yellowstone National Park. The water chemistry of several features is monitored to document changes and to understand or infer variations in hydrothermal plumbing systems.

Included in this year's sampling at Norris Geyser Basin was Colloidal Pool in Porcelain Basin. Colloidal Pool usually contains opalescent teal-blue water, but in 2021 the appearance was opaque blue-brown water with a foamy surface (fig. 9). The 2021 sample had lower temperature and conductivity compared to previous samples collected in 1998 and 2018 (table 1), which indicates a decrease in the flux of thermal water flowing into the pool. This shift in water chemistry at a thermal feature is not uncommon and may be a result of the interaction between the level of the water table, amount of boiling of deep geothermal waters, subsurface fluid flow paths (controlled by precipitation of hydrothermal minerals and seismicity), and variable mixing with meteoric or other water types.

## Geology

Geologic research in Yellowstone National Park is focused on interpreting the rock record as a means of better understanding conditions that preceded and accompanied past volcanic eruptions and hydrothermal explosions. The primary



**Figure 9.** Photograph looking north from the boardwalk toward Colloidal Pool in Norris Geyser Basin. Photograph by Mary Dwyer on August 1, 2021, used with permission.

**Table 1.** Temperature, pH, and conductivity measurements at Colloidal Pool in Norris Geyser Basin, Yellowstone National Park.

[°C, degrees Celsius;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter]

Date	Temperature (°C)	pH	Conductivity ( $\mu\text{S}/\text{cm}$ )
June 26, 1998	67.1	2.57	2,200
August 22, 2018	73.7	3.84	2,520
June 16, 2021	45.4	2.64	1,810

tools for this work include mapping rock compositions and structures, as well as determining the ages of specific rock units. This work established the foundation for understanding eruptions in the Yellowstone region (see sidebar on geology of Yellowstone Plateau on p. 20–21) and continues to be refined as new analytical tools become available and as mapping becomes sufficiently detailed to better identify small-scale features.



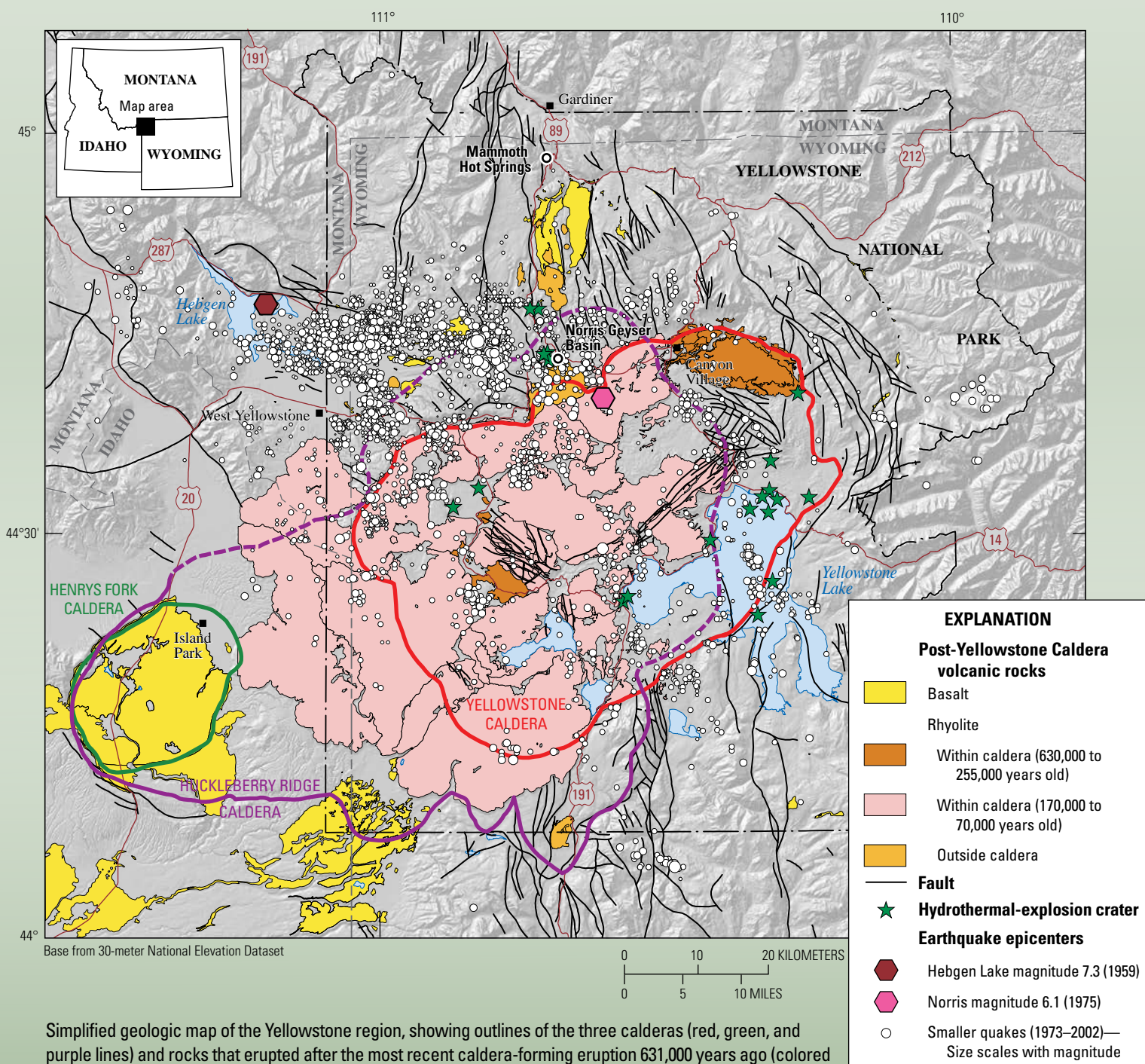
## Geology of the Yellowstone Plateau

The Yellowstone Plateau volcanic field developed through three volcanic cycles that span 2 million years and include two of the world's largest known volcanic eruptions. About 2.1 million years ago, eruption of the Huckleberry Ridge Tuff produced more than 2,450 cubic kilometers (588 cubic miles) of volcanic deposits—enough material to cover the entire State of Wyoming in a layer 10 meters (30 feet)

thick—and created the large, approximately 75 kilometer (47 mile) wide, Huckleberry Ridge Caldera. A second cycle concluded with the eruption of the much smaller Mesa Falls Tuff around 1.3 million years ago and resulted in formation of the Henrys Fork Caldera. Activity subsequently shifted to the present Yellowstone Plateau and culminated 631,000 years ago with the eruption of more than 1,000 cubic kilometers (240 cubic

miles) of magma, forming the Lava Creek Tuff, and formation of the 45×85 kilometer (28×53 mile) Yellowstone Caldera.

The three extraordinarily large explosive volcanic eruptions in the past 2.1 million years each created a giant caldera and spread enormous volumes of hot, fragmented volcanic rocks via pyroclastic density currents over vast areas. The accumulated hot ash, pumice,



Simplified geologic map of the Yellowstone region, showing outlines of the three calderas (red, green, and purple lines) and rocks that erupted after the most recent caldera-forming eruption 631,000 years ago (colored areas). Modified from U.S. Geological Survey Fact Sheet 2005–3024 (Lowenstern and others, 2005).

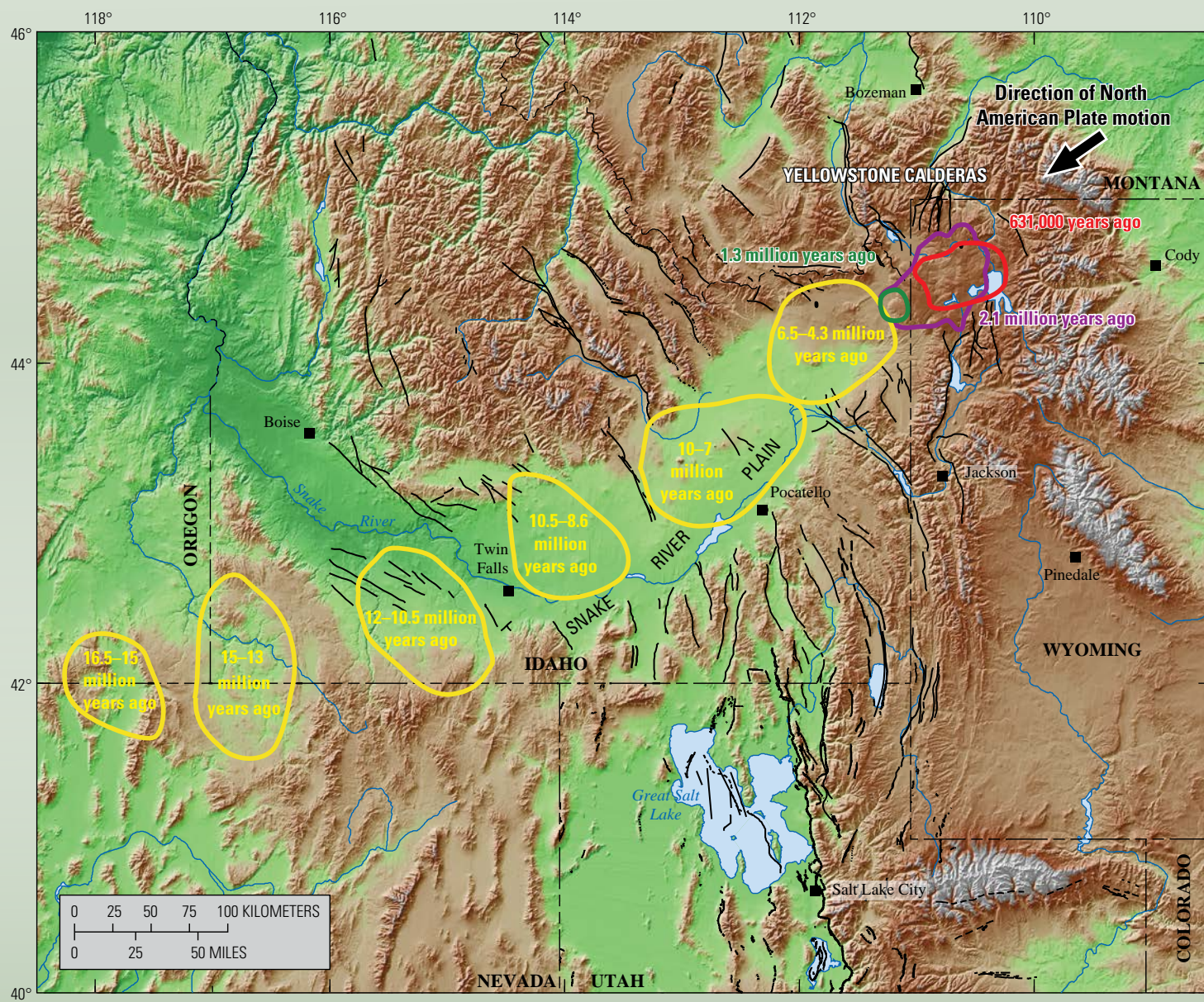


and other rock fragments welded together from their heat and the weight of overlying material to form extensive sheets of hard lava-like rock, called tuff. In some places, these welded ash-flow tuffs are more than 400 meters (1,300 feet) thick. The ash-flow sheets account for about half the material erupted from the Yellowstone region.

Before and after these caldera-forming events, volcanic eruptions in the Yellowstone region produced rhyolitic and basaltic rocks—including large rhyolite lava flows (pink and orange colors on

simplified geologic map on previous page), some smaller rhyolite pyroclastic flows in and near where the calderas collapsed, and basalt lava flows (yellow color on simplified geologic map) around the margins of the calderas. Large volumes of rhyolitic lava flows (approximately 600 cubic kilometers, or 144 cubic miles) were erupted in the most recent caldera between 170,000 and 70,000 years ago. No magmatic eruptions have occurred since then, but large hydrothermal explosions have taken place since the end of the last ice age in the Yellowstone region, 16,000–13,000 years ago.

Yellowstone Caldera's volcanism is only the most recent in a 17-million-year history of volcanic activity that has occurred progressively from near the common border of southeastern Oregon, northern Nevada, and southwestern Idaho to Yellowstone National Park as the North American Plate has drifted over a hot spot—a stationary area of melting within Earth's interior. At least six other large caldera-forming eruptions; the calderas are no longer visible because they are buried beneath younger basaltic lava flows and sediments that blanket the Snake River Plain.



Volcanic centers are outlined where the Yellowstone Hot Spot produced one or more caldera eruptions—essentially “ancient Yellowstones”—during the time periods indicated. As the North American Plate drifted southwest over the hot spot, the volcanism progressed northeast, from the common border of southeastern Oregon, northern Nevada, and southwestern Idaho 16.5 million years ago and reaching Yellowstone National Park about 2 million years ago. Mountains (whites, browns, and tans) surround the low elevations (greens) of the seismically quiet Snake River Plain. The low elevations of the Snake River Plain mark the alignment of past calderas that have since been filled in by lava flows and sediments. Black lines show faults within the region. Modified from Smith and Siegel (2000) with permission.



## Summary of Geology Activities in 2021

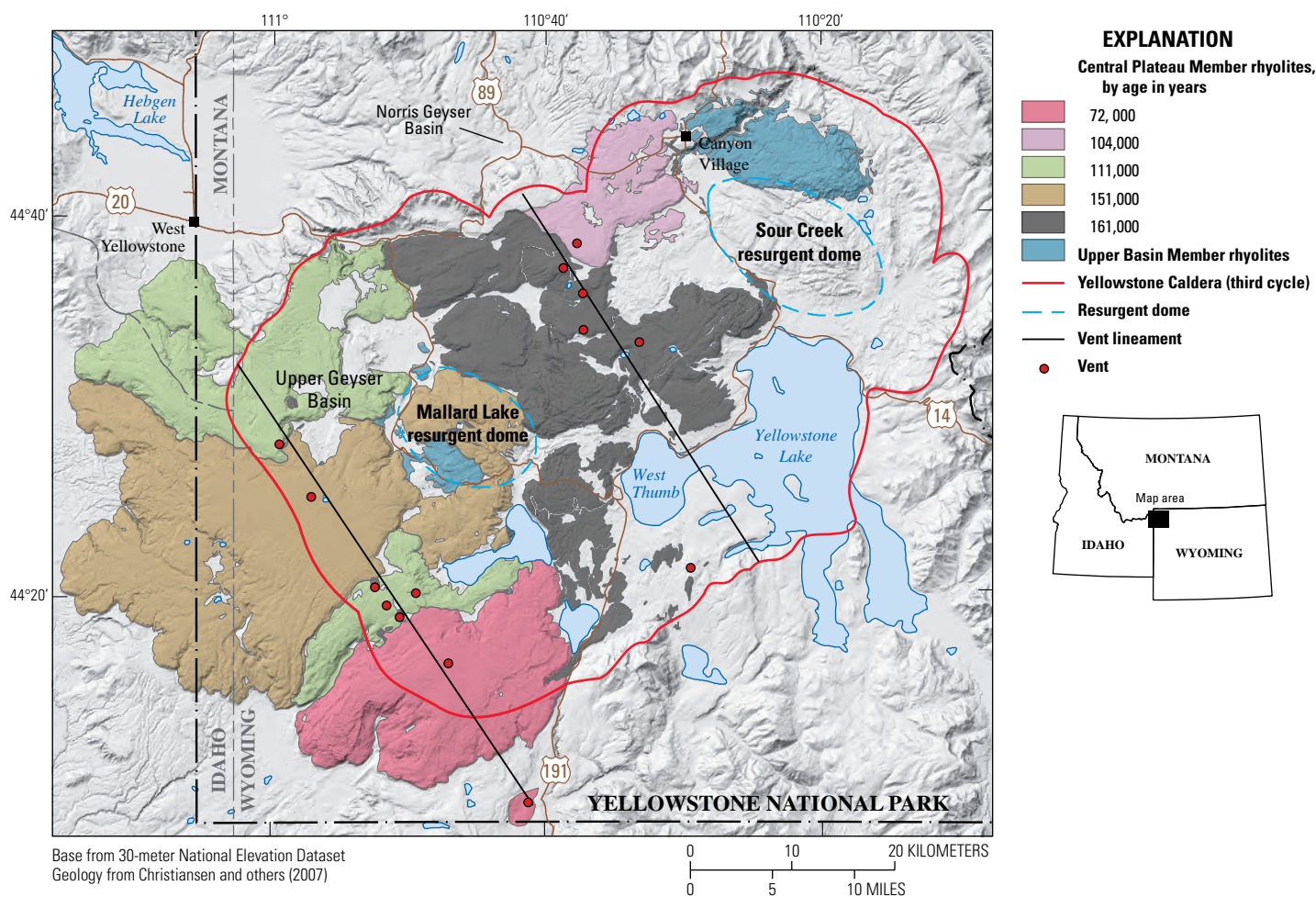
Despite the COVID-19 pandemic, progress was made on several independent yet related laboratory- and field-based geologic studies. Laboratory work focused on dating rhyolite and basalt lava flows in Yellowstone National Park to better constrain the timing of post-caldera volcanic eruptions. Field work included investigating some of the boundary-problem issues in existing geologic maps, correcting maps of geologic units around Mount Everts and the Sour Creek resurgent dome, and investigating the characteristics of hydrothermal explosion craters in the Lower Geyser Basin. Geologists also sampled hydrothermal travertine within Yellowstone Caldera to understand the origin of the deposits.

## Understanding the Recent Volcanic History of the Yellowstone Region

During 2021, work to constrain the timing and composition of volcanism within the Yellowstone Plateau volcanic field continued. The goals of this work are threefold: (1) develop a robust and precise eruptive history for the period after the formation of

Yellowstone Caldera about 631,000 years ago, (2) investigate the dynamics and physical state of the Yellowstone Caldera magma reservoir during intra-caldera eruptive episodes, and (3) provide a robust age and chemical dataset for rhyolites that erupted after formation of Yellowstone Caldera to aid in determining the history of glacial deposits in and around the caldera. Field work was carried out in July and October of 2021 to collect samples to further these efforts.

To achieve these goals, YVO geologists applied modern, high-precision argon-argon ( $^{40}\text{Ar}/^{39}\text{Ar}$ ) dating methods to samples from the Central Plateau Member of the Plateau Rhyolite and basalts in the Yellowstone region to constrain their volcanic eruption ages. In total, six rhyolite samples were dated via the  $^{40}\text{Ar}/^{39}\text{Ar}$  method in 2021. Seven basalts located west of Yellowstone Caldera were also dated via the  $^{40}\text{Ar}/^{39}\text{Ar}$  method. New  $^{40}\text{Ar}/^{39}\text{Ar}$  eruption ages for the Central Plateau Member rhyolite samples are consistent with prior results that indicate post-caldera volcanism from 170,000 to 72,000 years before present at Yellowstone Caldera was characterized by five brief eruption clusters where multiple (as many as seven) bodies of eruptible rhyolite were generated and erupted in short timespans from vents spanning large distances (more than 40 kilometers [25 miles])



**Figure 10.** Shaded-relief map of Yellowstone Caldera showing the age and location of intra-caldera rhyolites that erupted after the Lava Creek Tuff. The Upper Basin Member of the Plateau Rhyolite (blue) is the first episode of post-Lava Creek Tuff volcanism, occurring from approximately 630,000 to 255,000 years before present. The Central Plateau Member of the Plateau Rhyolite erupted in a second episode and is shown by volcanic eruption age estimated via recent high-precision  $^{40}\text{Ar}/^{39}\text{Ar}$  dating methods. The black solid lines represent structurally controlled vent zones from which the Central Plateau Member erupted (individual vent locations shown as red dots).



apart) (fig. 10). Preliminary  $^{40}\text{Ar}/^{39}\text{Ar}$  eruption ages for basalts span a wide range from about 1.022 million years to 35,000 years old.

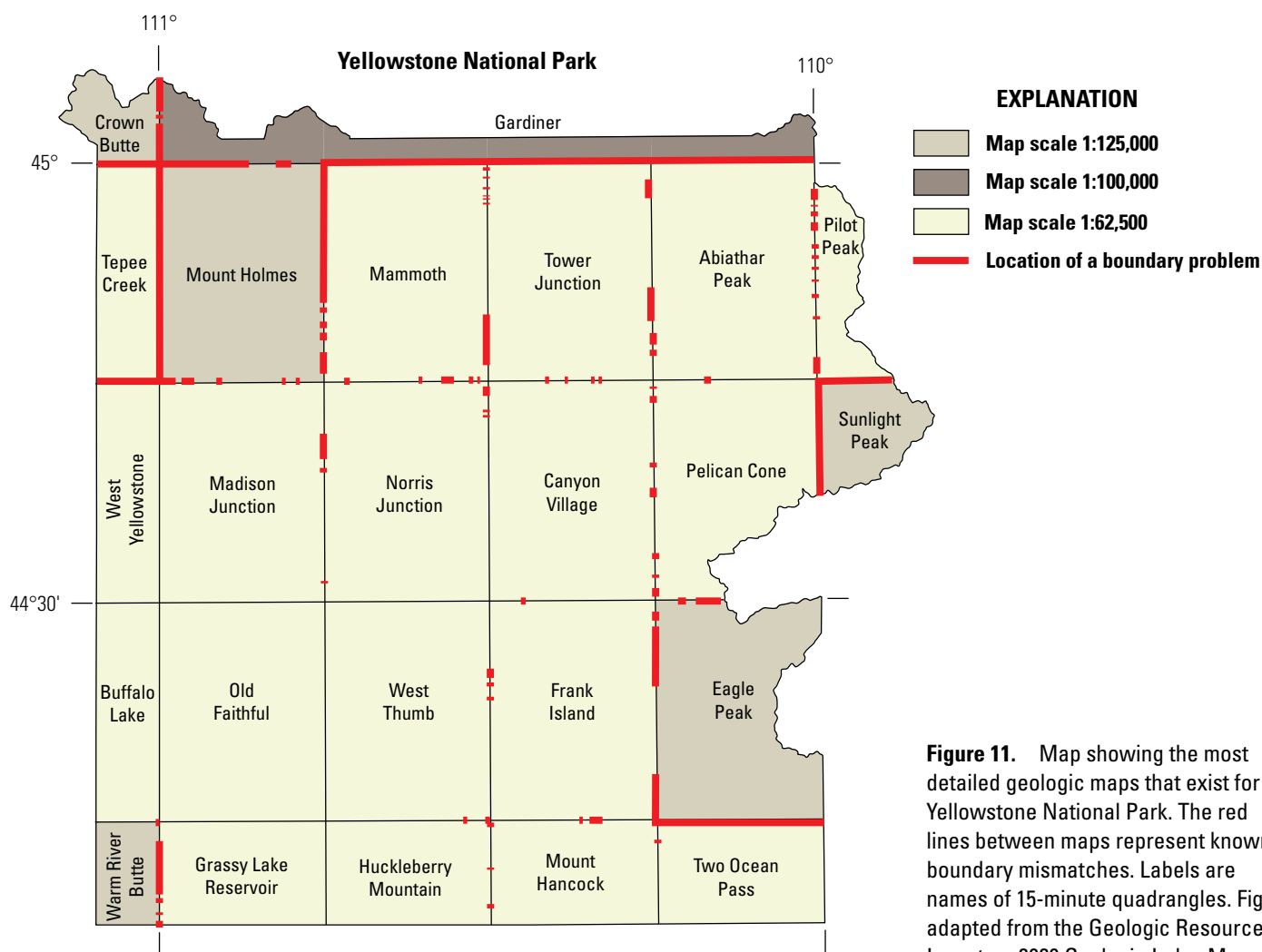
Several additional datasets were generated to support the new geochronologic results. Lead-isotope and major-element compositions of sanidine crystals hosted within seven rhyolites that erupted at essentially the same time 161,000 years ago were measured. Lead-isotope analyses were performed by Katherine Hewitt and Kari Cooper at the University of California, Davis, and major-element compositions of sanidine crystals were measured by Nicole Thomas at the USGS California Volcano Observatory in Menlo Park. In addition, paleomagnetic samples were collected from five of these rhyolites in October 2021. Integrating geochronologic, geochemical, and paleomagnetic data will provide a means to test whether the seven rhyolites that erupted 161,000 years ago were derived from a common, interconnected magma body or were erupted from discrete, chemically distinct magma bodies. Furthermore, the combination of  $^{40}\text{Ar}/^{39}\text{Ar}$  dating and paleomagnetic analysis will provide a means of estimating the duration of these brief volcanic eruption clusters.

In addition to rhyolite and basalt eruptive units, five samples of glacial erratic blocks (rocks transported a far distance from their origin by a glacier) were collected in July 2021. These glacial deposits are composed of young Yellowstone Caldera rhyolite

flows. Work is underway to measure  $^{40}\text{Ar}/^{39}\text{Ar}$  eruption ages and chemical compositions of these erratic blocks to determine their history—the eruptive units from which they derive and their formation ages. The results of this study can provide information on the flow path of past glaciers across the Yellowstone Plateau.

## Geologic Mapping in Yellowstone Caldera

Starting in 2020, a team of geologists from Montana State University (MSU), in collaboration with Yellowstone National Park, set out to compile a uniform and high-resolution geologic map of the park. However, when the existing geologic maps of Yellowstone National Park (both published and unpublished maps completed at different times and scales by different geologists for different purposes) were compiled, it became clear that many of the geologic maps did not match along their shared boundaries. This is not an uncommon or unexpected occurrence, as compiling maps made by different authors with varying mapping objectives is bound to result in some mismatch. In the case of Yellowstone National Park, 485 boundary problems were identified and needed to be resolved before a new map can be produced; most mismatches occur between maps of different scales (fig. 11).



**Figure 11.** Map showing the most detailed geologic maps that exist for Yellowstone National Park. The red lines between maps represent known boundary mismatches. Labels are names of 15-minute quadrangles. Figure adapted from the Geologic Resources Inventory 2020 Geologic Index Map of Yellowstone National Park.



Over the last two field seasons (2020 and 2021), the research group from MSU visited about 60 locations with boundary issues and ultimately resolved 30; this number reflects the challenges of working off trail in a heavily forested and glacially altered landscape. Through these field visits, geologists learned important lessons regarding the existing geologic maps and their relations to one another. To help assess and evaluate the complex nature of the boundary problems, they were divided into four types:

1. “Detail difference” problems, defined as two maps using a different naming scheme for the same unit (264 instances),
2. “Contact offset” problems, where the contact between rock units is misaligned across the boundary (105 instances),
3. “Full stop” problems, where a mapped rock unit crosses the map boundary but does not appear on the adjacent map (110 instances), and
4. “Double take” problems, where a mapped rock unit stops short of the map boundary but reappears on the adjacent map (6 instances).

Although geologists will not be able to correct all of the identified boundary issues by the end of the project in summer 2022, the effort has highlighted that there is ample room for new mapping projects to take place in Yellowstone National

Park. This leaves the opportunity wide open for graduate students, USGS geologic mappers, State survey geoscientists, and many others to begin efforts of mapping the park at a higher resolution. Nine quadrangles in the park have not been mapped at the standard 1:62,500 scale; a high priority is to remap these areas at that scale to match the maps published in 1972. From there, a new comprehensive geologic map of the whole park could be published at a consistent scale.

## Geology of Mount Everts

Mount Everts (fig. 12) is located along the northern border of Yellowstone National Park near Mammoth Hot Springs, spanning the divide between Montana and Wyoming. It is currently represented by two geologic maps, generally aligned with State boundaries, whose mapped interpretations of Mount Everts rock types and designated formation names disagree. The northern map, the Gardiner 1:100,000-scale quadrangle (Berg and others, 1999), shows Mount Everts as Archean schist and hornfels (mapped as unit **Ash** in fig. 13) whereas the southern map, an unpublished mylar map of the Mammoth 1:62,500-scale quadrangle (mapping was completed in 1972), depicts the area as a series of Upper Cretaceous sedimentary rocks (mapped as units **Kl**, **Kev**, and **Ke** in fig. 13). Initial investigation in 2021 of the northern terminus of Mount Everts quickly determined that it is composed of sedimentary



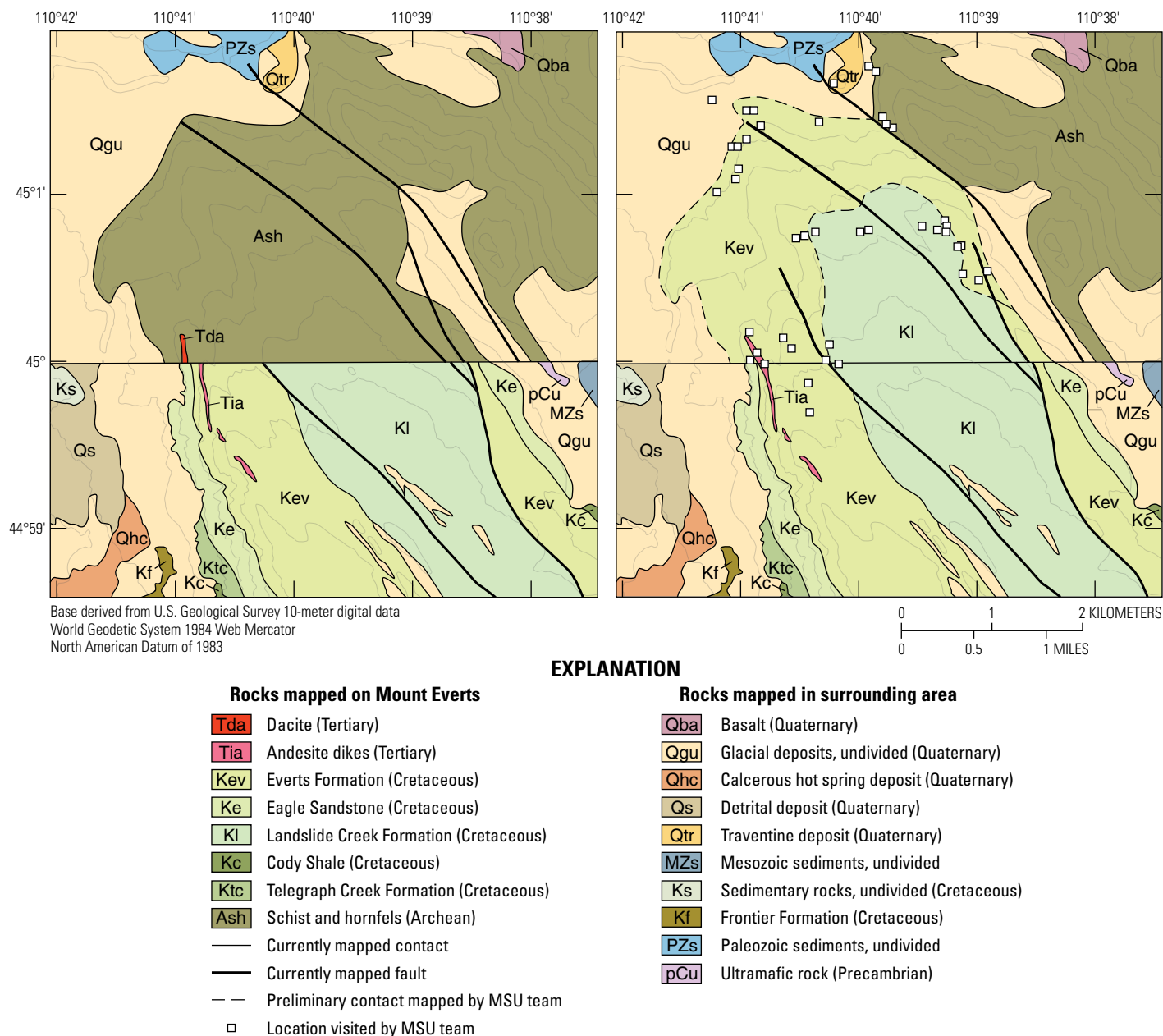
**Figure 12.** Photograph looking north at the southern face of Mount Everts, located on the northern boundary of Yellowstone National Park. Photograph by Natali Kragh of Montana State University on May 19, 2021.



rock. Samples were taken from the northeast side of Mount Everts to petrologically compare units across maps (fig. 13). Hand samples and microscope thin sections made from the samples closely matched descriptions of the Upper Cretaceous sedimentary units mapped on the Mammoth 1:62,500-scale quadrangle. The thin sections were also compared to samples taken from mapped Upper Cretaceous units (unit Kl on fig. 13) on the Montana map to determine if there are striking petrologic differences that might have led to the contrasting unit designations. No obvious differences were detected in

hand samples or thin sections between rocks found on Mount Everts and rocks mapped Upper Cretaceous rocks (unit Kl).

To further confirm geologic unit relations between maps, as well as to remap the northern part of Mount Everts, six more thin sections are being analyzed, and field work will continue through 2022. Future work in the area will concentrate on the southern part of the mountain to assess contact locations between units. This work highlights the importance of reassessing older geologic maps and making necessary updates, particularly along shared boundaries with other maps.



**Figure 13.** Geologic maps of the northern part of Mount Everts in north-central Yellowstone National Park. *A*, The most current largest scale maps of Mount Everts. The northern map is the Gardiner 1:100,000-scale quadrangle (Berg and others, 1999) and the southern map is an unpublished mylar map from 1972 of the Mammoth 1:62,500-scale quadrangle. *B*, Preliminary map showing the areas visited by the Montana State University (MSU) team and their subsequent interpretations of the geology on the northernmost part of Mount Everts. Mapped unit contacts remain dashed (indicating their approximate locations) as there is more work to be done, specifically in locating the Cretaceous Eagle Sandstone (unit Ke) in the north and in correcting the boundary on the eastern side of the mountain.

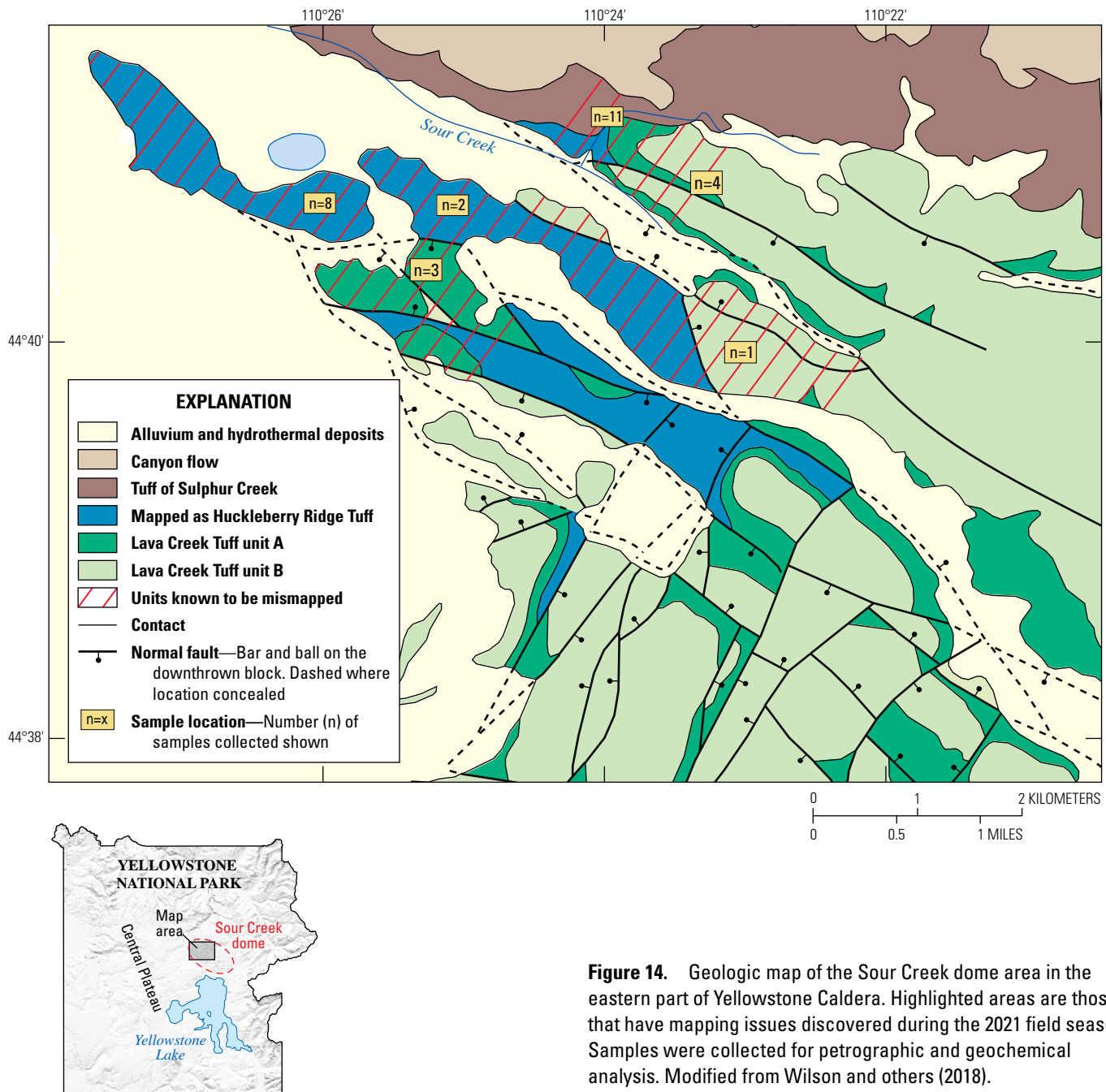


## Sour Creek Dome Remapping

The approximately 1,000-cubic-kilometer (240-cubic-mile) Lava Creek Tuff erupted during the youngest major caldera-forming event of the Yellowstone volcanic system about 631,000 years ago. It generated two pyroclastic flow deposits (called ignimbrites), A and B, with an accompanying exceptionally widespread fall deposit distributed over the western United States (Wilcox and Naeser, 1992). On the Sour Creek resurgent dome on the east side of Yellowstone Caldera, recent age dating on ignimbrite units that were thought to be from the Huckleberry Ridge Tuff, about 2.1 million years old, have revealed ages consistent with those of the Lava Creek Tuff ignimbrite (Wilson

and others, 2018). These results imply the overall Lava Creek Tuff eruption is more complex than currently thought.

Field and laboratory work in 2021 of the two newly dated deposits reveal that they are distinct from units A and B of the Lava Creek Tuff and are therefore inferred to represent separate volcanic outbursts related to the Lava Creek Tuff eruption and formation of Yellowstone Caldera. MSU geologists are working to resolve the nature of the newly dated units, document their extent and source area(s), estimate their volumes, and determine how they relate geochemically to units A and B of the Lava Creek Tuff. This work includes remapping and documenting the newly recognized Lava Creek Tuff units in and around Sour Creek dome to compare them



**Figure 14.** Geologic map of the Sour Creek dome area in the eastern part of Yellowstone Caldera. Highlighted areas are those that have mapping issues discovered during the 2021 field season. Samples were collected for petrographic and geochemical analysis. Modified from Wilson and others (2018).



against previously documented units A and B of the Lava Creek Tuff. Thus far, it appears that much of what has been mapped as older Huckleberry Ridge Tuff in the Sour Creek dome area is actually one of the two newly defined units, which appears to dominate the region (fig. 14). The new units can be distinguished from other ignimbrite units in the area by the presence of dark scoria. Additional work planned for summer of 2022, including incorporation of undergraduate researchers, will attempt to remap the entire Sour Creek dome.

## Mapping Twin Buttes Hydrothermal Explosion Crater in Lower Geyser Basin

Hydrothermal (steam-driven) explosions are forceful water eruptions sourced from shallow hydrothermal systems that can throw rock, mud, steam, and boiling water as far as 4 kilometers (2.5 miles) from the explosion site. They are driven by heat and H<sub>2</sub>O phase changes (from water to steam) in the shallow subsurface and do not involve any magma. More than 100 small hydrothermal explosions have taken place in Yellowstone National Park during the last approximately 200 years, and at least 18 large hydrothermal explosions that created craters more than 300 meters (about 1,000 feet) in diameter have occurred since the last glaciation, which ended about 16,000–13,000 years ago. A few small explosions have even occurred during recorded history and were well documented, like Excelsior Geyser in the late 1800s and Porkchop Geyser in 1989.

Despite the significant hazard posed by hydrothermal explosions, much remains unknown about these events. For example, of the identified prehistoric hydrothermal explosion events in Yellowstone National Park, all but four have dates of emplacement that are estimated rather than directly measured. YVO researchers have been working to determine age constraints on two notably large hydrothermal explosions located in Lower Geyser Basin: Twin Buttes and Pocket Basin. In 2021, new mapping of the Twin Buttes explosion crater (fig. 15) was carried out to constrain the size of the explosion and the topography of the ground surface before the event. Samples were collected for luminescence and cosmogenic isotope exposure dating from both the Twin Buttes and Pocket Basin explosion craters. The field work provided an opportunity for interns and undergraduate students to participate in field activities, and results in the coming year may provide the first age constraints on the formation times of these two large hydrothermal explosion events.

## Hydrothermal Travertine Within Yellowstone Caldera

Travertine is a variety of calcium carbonate that forms as hot water interacts with old, marine limestone and magmatic gases at depth. As the water rises and emerges at the surface, the decrease in pressure causes carbon dioxide

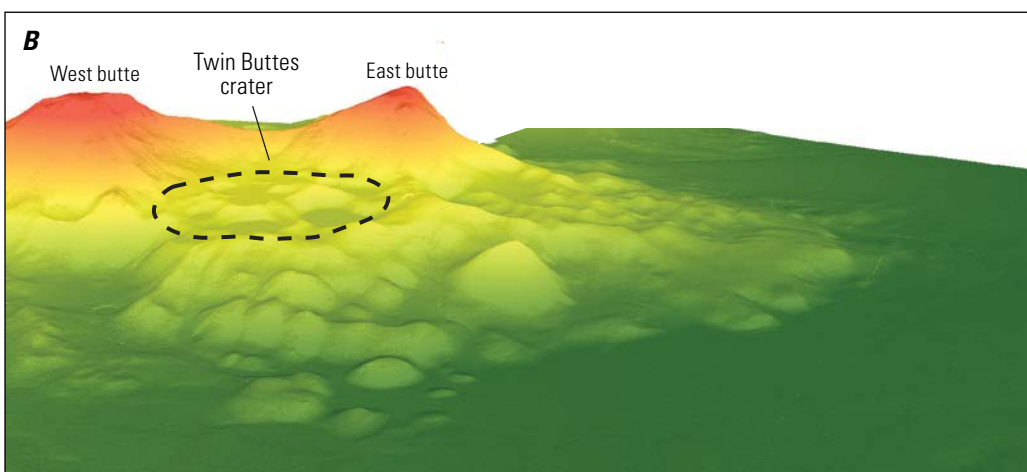
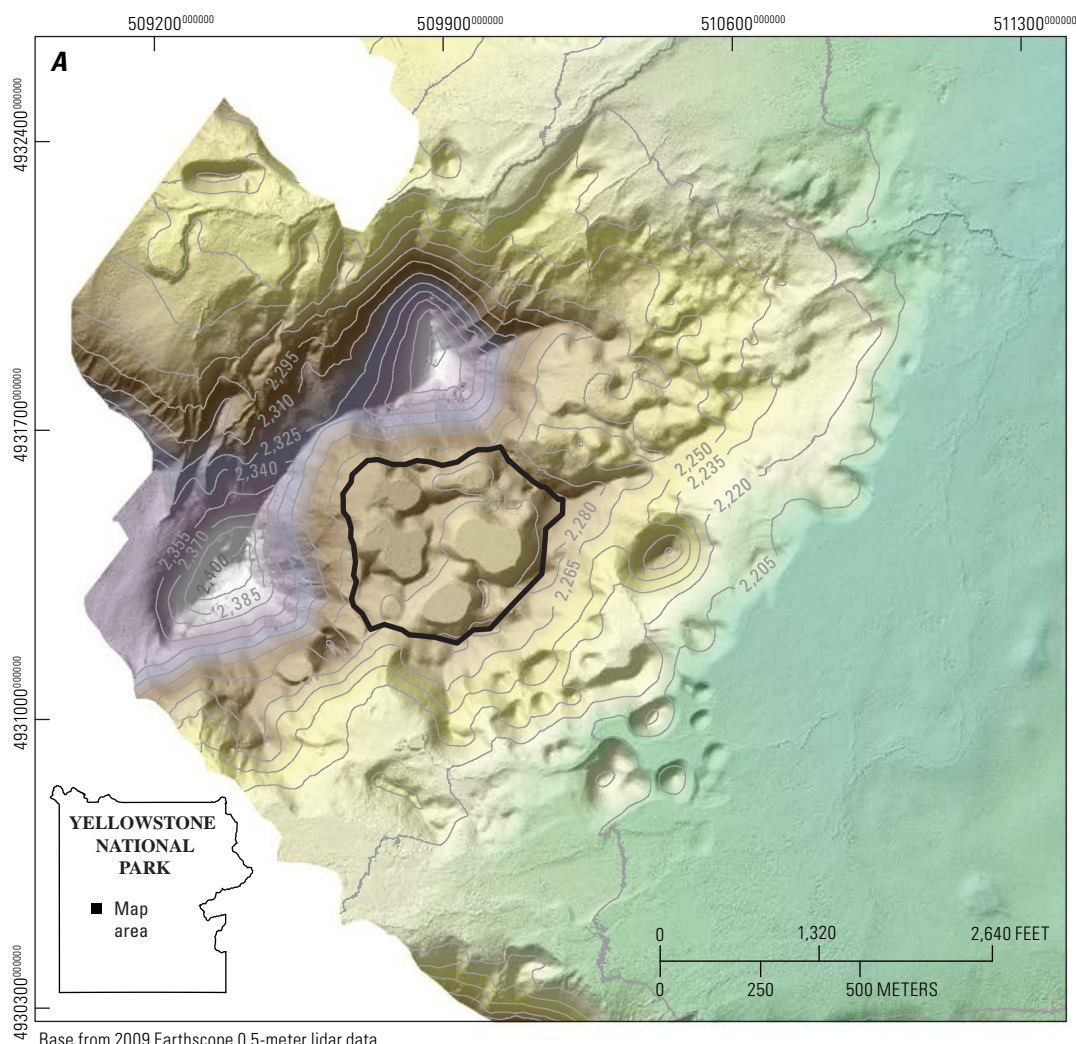
to degas from the water and calcium carbonate to precipitate. Mammoth Hot Springs, located near the northern boundary of Yellowstone National Park and well outside Yellowstone Caldera, is well known for large deposits of hydrothermal travertine that form white terraces tens of meters high. Less well-known locations of travertine deposits also exist around the park within Yellowstone Caldera, although they are much smaller than the Mammoth Hot Spring deposits and have not been as well studied. Four such locations are Firehole Lake in Lower Geyser Basin (fig. 16), Hillside Springs in Upper Geyser Basin, Terrace Spring near Madison Junction, and the informally named Fairyland basin in the upper Pelican Valley.

YVO researchers collected travertine samples from the first three of these locations in the summer of 2021 to investigate their ages and the reasons for the formation of these relatively rare deposits of hydrothermal travertine. It is hypothesized that within-caldera travertine deposition can be activated or deactivated according to changing climatic conditions, with deposition occurring when there are anomalously large influxes of cold meteoric water from deglaciation or cold, wet climatic conditions, and no deposition during arid periods. The ages of travertine deposits in the Yellowstone region might therefore be used to constrain the timing of climatic events that affected the Yellowstone region since the last ice age (locally called the Pinedale glaciation, which occurred 22,000–13,000 years ago). Today, climatic conditions are warm and arid, so there is no significant deposition of travertine within these areas. Analysis of these old travertine deposits may show whether travertine deposition through time is related to regional changes in climate that transformed the chemistry of the hydrothermal system in both the Upper and Lower Geyser Basins.

## Sample Collection Database

Since the USGS began detailed geologic investigations of Yellowstone National Park, numerous samples have been collected for various types of analyses, including age determination, chemical composition, and physical structure. Many of these samples were collected before modern geographic information systems were available, so the only information about sample locations and other details were in hand-written field notes and annotated maps. To preserve geologic sample information—especially that collected by Robert L. Christiansen and used in his comprehensive study of the geology of the Yellowstone region (Christiansen, 2001)—sample site locations in Yellowstone National Park and surrounding areas were digitized and translated into a digital database. The database, which includes information about hand samples, thin sections, and mineral separates, provides a reference to the geologic information for individual samples and the approximate locations of sample sites that were used to map the geology of the Yellowstone region. The database (Robinson and others, 2021) is publicly accessible online at <https://doi.org/10.5066/P94JTACV>.





**Figure 15.** A, Color shaded relief of the Twin Buttes hydrothermal explosion crater in Lower Geyser Basin. High elevations are whites and purples, low-lying areas are greens and yellows. The explosion crater is outlined in black and contains multiple smaller craters that are currently filled with water to create small, perched lakes. Two large buttes (Twin Buttes) stand above the crater to the north and west, and the area to the east and south of the crater is surrounded by complex topography of explosion debris, slump blocks, and hills that existed before the explosion. Gray lines show elevation contours; interval is 15 meters. B, Oblique view of the colored digital elevation model looking north. The circumference of the explosion crater (dashed line) is 645 meters (2,120 feet).





**Figure 16.** Photograph of a horizontally bedded travertine terrace deposit near Firehole Lake in the Lower Geyser Basin of Yellowstone National Park. View is looking east toward the Mallard Lake lava flow (forested ridge in the distance) and the Elephant Back lava flow (forested ridge on the left); Firehole Lake is behind the photographer. Actively steaming thermal features can be seen in the distance up the valley. Scale at lower right is in centimeters. U.S. Geological Survey photograph by Lauren Harrison in 2021.

## Yellowstone Lake Studies

Yellowstone Lake (fig. 17) is the largest high-altitude (above 2,100 meters, or about 6,900 feet) freshwater lake in North America. It covers about 341 square kilometers (132 square miles) of Yellowstone National Park and hosts a variety of hot springs and hydrothermal areas beneath its surface. Long a subject of research, investigations of hydrothermal processes on the lake floor got a boost in 2015 with the start of the Hydrothermal Dynamics of Yellowstone Lake (HD-YLAKE) project, funded by the National Science Foundation with support from the USGS, Yellowstone National Park, Yellowstone Foundation, and Global Foundation for Ocean Exploration (Sohn and others, 2017). Although funding concluded in 2019, HD-YLAKE scientists continue to analyze data collected during the project and develop and pursue new lines of study. The overall aim of the research, which involves scientists from numerous institutions around the world, is to understand how Yellowstone Lake hydrothermal systems respond to geological and environmental changes by compiling observations of temporal changes in hydrothermal fluid temperature and composition, heat flow, seismicity, water-column processes, and microbial communities that inhabit the vent fields. Field strategies take a two-pronged approach: (1) geophysical and geochemical monitoring of the active hydrothermal system and (2) analyses of sediment cores to study the postglacial (approximately

14,000-year) history of sedimentary, tectonic, and hydrothermal activity beneath the lake.

### Summary of Yellowstone Lake Studies in 2021

In 2021, scientific results included studies of lake cores that were collected in 1992, 2016, and 2017 and that contain evidence of past hydrothermal explosions, faulting, and hydrothermal doming. In addition, detailed study of an 11.82-meter (38.78-foot) sediment core from the Lake Hotel graben in northern Yellowstone Lake provided a comprehensive picture of paleoenvironmental conditions from the past 10,000 years. New sediment cores also were collected in August 2021 to better understand hydrothermal activity occurring on the floor of Yellowstone Lake.

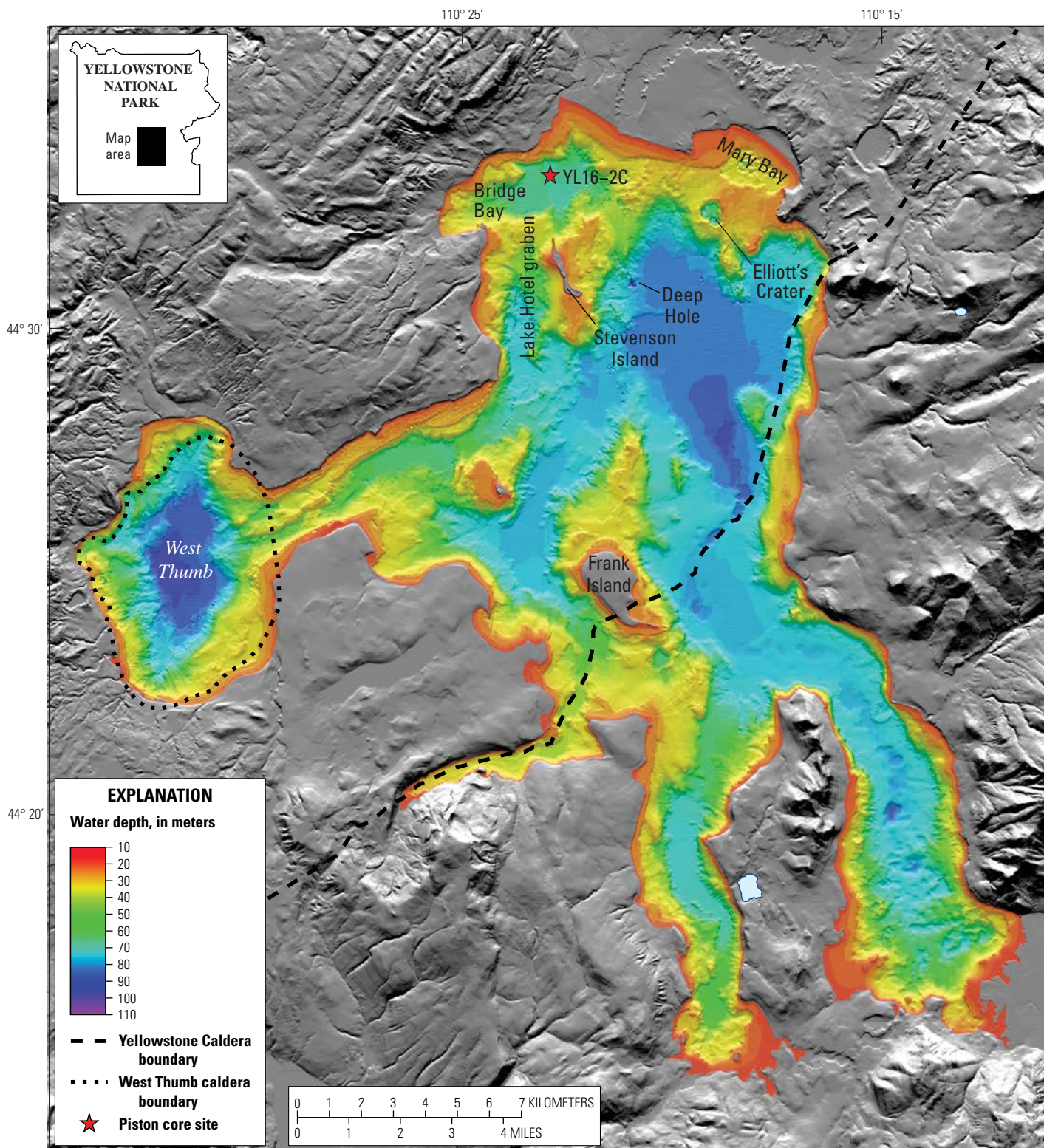
### Explosion Deposits in Lake-Bottom Sediments

An important goal of the HD-YLAKE project and subsequent studies has been to understand the characteristics, distribution, depositional processes, and triggers of large hydrothermal explosions in and around Yellowstone Lake. Of 18 sedimentary cores collected from the lake floor, 17 contain evidence for hydrothermal explosion deposits that range in age from 13,000 to 160 years old. At least 15 explosion deposits have



been identified, and most cores also contain interbedded ash layers from past volcanic eruptions in the Cascade Range—the eruptions of Mount Mazama (Crater Lake) 7,600 years ago and Glacier Peak 13,600 years ago—that provide marker beds for determining the ages of explosions within Yellowstone National Park.

Yellowstone Lake is dominated by two different types of hydrothermal systems: (1) alkaline-chloride areas, which involve neutral to slightly basic waters and are typified by geyser systems like Old Faithful and Steamboat Geysers, and (2) vapor-dominated areas, which emit acidic gases and are characterized by mineral



Base from U.S. Geological Survey Scientific Investigations Map 2973 by Morgan and others (2007)

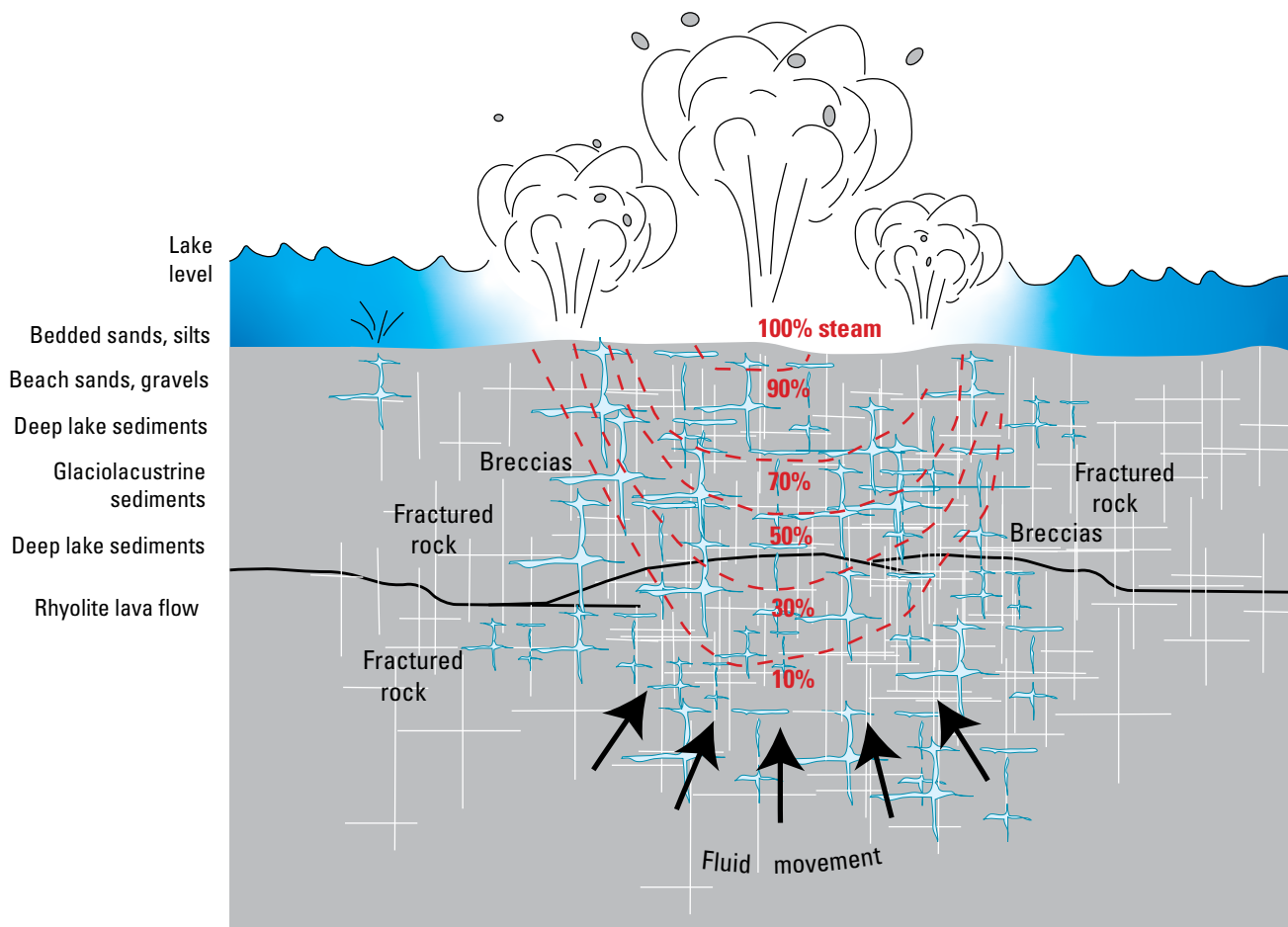
**Figure 17.** Bathymetric map of Yellowstone Lake showing the locations of coring site YL16-2C and the areas known informally as Deep Hole and Elliott's Crater.



alteration that results in clay formation. The second type of hydrothermal system is exemplified by the vent area informally known as the Deep Hole on the lake floor. Hydrothermal explosions from these systems require a sudden drop in pressure, which results in rapid expansion of high-temperature fluids that then causes fragmentation, ejection of steam, hot water, mud, and altered clay and rock fragments, and crater formation. The largest hydrothermal explosions in the Yellowstone region occur from alkaline-chloride thermal areas because the thermal water flashes to steam during hydrothermal explosions, producing much more energetic events than simple expansion of the already vapor-dominated thermal areas in the lake. Larger explosions may be initiated by seismicity, faulting, deformation, or, in Yellowstone Lake, rapid lake-level changes. Two enormous explosion events in Yellowstone Lake were triggered quite differently. The area informally named Elliott's Crater (first discovered by USGS bathymetric mapping in 1999) formed about 8,000 years ago, probably from a major seismic event that ruptured a hydrothermal dome. In contrast, the Mary Bay explosion 13,000 years ago may have been triggered by a sudden drop in lake level related to a cascade of processes, which began with a large earthquake on the

lake floor causing a tsunami that eroded the lake's outlet channel (Morgan and others, 2022).

The hydrothermal explosion deposits recorded in the sediment on the floor of Yellowstone Lake reveal details of the explosion processes and indicate the following: (1) the explosion deposits are distinct from other lake sediments in their physical characteristics, trace element composition, magnetic susceptibility, and density; (2) the ejecta from these explosions are extensively altered, indicating that pervasive hydrothermal activity occurred prior to the explosions; (3) physical sorting of the deposits in the piston cores indicates the explosion ejecta settled through the water column; (4) the large crater-producing hydrothermal explosion events (which resulted in craters more than 500 meters [1,640 feet] in diameter) generated multiple explosion pulses, separated by decades to hundreds of years; (5) the intensity of the explosions from a specific crater decreased over time; (6) the distribution and cumulative thickness of the deposits indicate that some explosions are directional; and (7) the alkaline-chloride systems produce large top-down explosion events (fig. 18) (Morgan and others, 2009, 2022).



**Figure 18.** Schematic diagram illustrating a large, alkaline-chloride hydrothermal explosion in Yellowstone Lake generated by a sudden pressure drop at the surface, which allows fluids at the boiling point to flash to steam. This pressure drop is transmitted downward through hydraulically connected fractures, starting a series of instantaneous and cascading explosions that result in the expulsion of large amounts of fractured rock, altered clay, boiling muds, water, and steam and production of a large crater. As the pressure drop propagates downward, a progressive decrease in the amount of steam is produced until, at some depth, no steam is produced. Included on the diagram is a schematic subsurface stratigraphy beneath the Mary Bay explosion crater. Modified from Morgan and others (2009, 2022).



## Analyses of Paleo-environmental Conditions from Yellowstone Lake Sediment Core

Sediment at the bottom of lakes has proven to be an excellent stratigraphic record of conditions in the past. For the Greater Yellowstone Ecosystem, sediment cores collected from Yellowstone Lake provide a basis to understand how climate in this basin has changed over the past 10,000 years, and how the environment has been affected (Brown and others, 2021).

A composite 11.82-meter-long (38.78-foot-long) sediment record collected from the northern part of Yellowstone Lake (site YL16–2C in fig. 17) was analyzed using biological and geochemical indicators to investigate the paleo-environmental evolution of the lake and its catchment in response to climatic conditions. Oxygen isotopes from diatom frustules (the hard and porous cell walls of diatoms, which are a form of algae) were analyzed to reconstruct climate changes over the past 10,000 years, and pollen, charcoal, diatom assemblages, and biologically generated silica provided information on terrestrial and lake responses to those climatic changes.

The long-term trends recorded in the terrestrial and lake ecosystems indicate that most changes were gradual and caused by slow changes in the seasonal cycle of solar energy input. This led to warm, dry summer conditions early in the record (9,900–6,300 years ago) and resulted in an open forest, small and frequent fires, high evaporation rates in summer, early spring snowmelt, generally low nutrient availability, and early melting of ice from the lake. Over time, the climate progressively changed to cooler and wetter conditions. The middle part of the record (6,300 to 3,000 years ago) reflects a cooling climate, resulting in denser forest establishment and larger fire episodes, as well as less summer evaporation and longer spring runoff. Further cooling and increased moisture in the most recent part of the record (3,000 years ago to a few hundred years ago) resulted in the development

of a closed forest with infrequent but large fire episodes, decreased summer evaporation, and high runoff into the lake. In addition to these gradual trends, a succession of short-term climate fluctuations occurred between 7,000 and 6,800 years ago and distinct warming occurred between 4,500 and 3,000 years ago and 1,000 to 700 years ago. These rapid climate fluctuations caused short-lived changes in algae and vegetation.

The climate history recorded in the sediment of Yellowstone Lake is typical of the overall Yellowstone region, where conditions were warmer and drier after the last ice age owing to higher solar energy input compared to more recent times. The climate became cooler and wetter throughout the record, reaching the relatively low temperatures and wet conditions of the time before the industrial revolution.

## New Sediment Cores from Yellowstone Lake

In August 2021, scientists collected sediment cores from several sites on the floor of Yellowstone Lake that were not previously investigated as part of the HD-YLAKE project. The goal of the new coring expedition was to use not only sediment composition, but also the composition of fluids found in pore waters extracted from the sediment to investigate lake-bottom hydrothermal activity. Nine cores (fig. 19) that varied in length from 14 to 59 centimeters (5.5 to 23 inches) were recovered using a gravity corer deployed from the research vessel *Annie*, a specially built boat designed for lake research. Thermal measurements from the cores were recorded by fitting the coring barrel with outriggers that carried temperature-measuring devices. The thermal measurements provide information on present-day heat flow that can reflect ongoing hydrothermal fluid flow.

The coring targets included several areas in the northern part of Yellowstone Lake (fig. 17), including: (1) two cores from the Mary Bay hydrothermal explosion crater—these contained fluids with temperatures as high as 91 °C (196 °F); (2) three cores from extensional fissures west of Stevenson Island to investigate present and past fluid flow and alteration of sediments in a region suspected of once being an active hydrothermal area; and (3) two cores from near Bridge Bay to assess pore water geochemistry and past hydrothermal explosions in that area. Preliminary results indicate pH values of pore fluids are 6.0–7.5, slightly acidic to slightly alkaline (neutral pH is 7.0). Some of the pH values are outside the normal range for lake water, indicating that the samples may be alkaline-chloride hydrothermal fluids, whereas others may be influenced by vapor-dominated fluids.



**Figure 19.** Photograph of pore waters from Yellowstone Lake sediment cores collected in August 2021. The pore waters are extracted through filtration devices into plastic syringes. Note that the second core from the left appears light in color because the plastic core liner was etched by very hot 91 °C (196 °F) fluids.

## Heat Flow Studies

The thousands of on-land thermal features of the Yellowstone region range in temperature from just a few degrees Celsius above the normal background temperature to well above boiling (as hot as 138 °C [280 °F]). Studies of thermal features are accomplished by ground-based



monitoring (including both occasional observations and continuous temperature monitoring), thermal-infrared remote sensing from satellite and aircraft, and proxy measurements of chloride in Yellowstone National Park's rivers (see sidebar on monitoring thermal changes on p. 34–35).

## Summary of Heat Flow Studies in 2021

The total radiative heat output from Yellowstone National Park's thermal areas in 2021, estimated from satellite thermal-infrared observations, was similar to that measured in previous years. Heat output based on chloride flux in Yellowstone National Park's rivers was slightly lower than measured in years past, although not significantly so. Together, the thermal-infrared and chloride-flux measurements indicate that the total thermal discharge remained relatively steady.

## Thermal-Infrared Remote Sensing

The methods of satellite thermal-infrared data processing and analysis underwent some changes in 2021 that resulted in estimates of the geothermal radiative power output that were higher than prior estimates. The new methods were also retroactively implemented on satellite thermal-infrared data from previous years, which also resulted in higher estimates. The first major change to the data processing and analysis workflow was the use of newly reprocessed Landsat-8 Collection 2 data—a major reprocessing of the Landsat-8 archive that improved absolute geolocation accuracy and radiometric calibration (Micijevic and others, 2021). The second change was the inclusion of newly mapped thermal areas and thermal drainages (defined as bodies of water that receive significant thermal input from nearby springs or underwater vents). Previously unmapped thermal areas on the north side of Mallard Lake dome (see “Recognition of Previously Unmapped Thermal Areas” section) added about 0.44 square kilometers (109 acres) to the database of thermal areas. Thermal drainages can be significant sources of geothermal radiant heat emission but had not been systematically included in past heat output estimates. Newly accounted thermal drainages constituted about 1.5 square kilometers (370 acres) of added area.

Data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument aboard the National Aeronautics and Space Administration's Terra satellite have been acquired intermittently over parts of the Yellowstone region since the year 2000. In 2021, there were 14 days with ASTER scenes (13 nighttime and 1 daytime) that covered parts of the Yellowstone region. Of these scenes, seven (50 percent) were cloudy, including all the winter and spring measurements acquired before June. Thus, no ASTER data were used to estimate park-wide thermal area heat flow for 2021. Landsat-8 thermal-infrared data cover the entire park in a single scene and have been regularly acquired since 2013, nominally every 16 days. In a given year, Landsat-8 will acquire about 44 scenes over the Yellowstone region (half

daytime and half nighttime), although nighttime scenes are not always acquired owing to on-orbit calibration events or data capacity and downlink limitations. In 2021, 19 Landsat-8 nighttime scenes were acquired, 9 of which were clear to mostly cloud free. There was only one clear nighttime scene acquired in the winter, on January 9, 2021 (fig. 20); those data were processed and analyzed for this report.

The results of analyses of the January 9, 2021, Landsat-8 thermal-infrared data were similar to analyses from previous years in that the same regions tended to be the warmest and most radiant. The thermal areas with notably high pixel temperatures, about 22 °C (40 °F) above background, were Sulphur Hills, Norris Geyser Basin, Lower Geyser Basin, and Astringent Creek. Two thermal drainages, Turbid Lake and Beula Lake, had the highest overall pixel temperatures, 24 to 26 °C (43 to 47 °F) above background. The same list of thermal areas and thermal drainages had the highest geothermal radiant emittance values, ranging from 82 to 97 watts per square meter. The thermal area with the highest total geothermal radiative power output (in megawatts), which tends to be the largest in area, was Lower Geyser Basin, emitting a whopping 713 megawatts. Other large areas with notably high geothermal radiative power output include Norris, Upper, and Midway Geyser Basins, Hot Spring Basin, Astringent Creek, and Roaring Mountain, with values ranging from 100 to 200 megawatts.

The total geothermal radiative power output summed for all of Yellowstone National Park's thermal areas was estimated from Landsat-8 thermal-infrared data acquired on January 9, 2021, as 2.5 gigawatts. This value, calculated only for the portions of thermal areas that were warmer than 2 standard deviations above the mean background temperatures, was higher than the values reported from the previous few years (table 2). This is due to a combination of factors, including the new processing and analysis methods mentioned above and the fact that these data were acquired in January, whereas data available from the previous few years (2017–2020) were acquired in March–May. Data acquired in the coldest winter months (for example, January and February) have lower background temperatures than in spring months (for example, March through May); therefore, removing the background removes less signal. Although background removal is required to avoid vastly overestimating the geothermal radiant heat output (Vaughan and others, 2014), it results in higher apparent thermal output values in data acquired in the winter when compared to data acquired in spring (table 2). All estimates of surface temperature, geothermal radiant emittance, and geothermal radiative power output from thermal-infrared remote sensing methods are underestimates, primarily owing to sub-pixel-scale thermal mixing and variable obscuration by steam. Data acquired at night in the winter, however, produce the least underestimated values, and are thus preferable (Vaughan and others, 2014). In other words, Yellowstone Caldera is not heating up; rather, scientists are improving their ability to retrieve more accurate estimates of how much heat is being radiated away from Yellowstone National Park's thermal areas.



## Monitoring Thermal Changes at Yellowstone National Park

A lot of heat is released in the Yellowstone region from thermal features like hot springs, geysers, mud pots, and fumaroles. Tracking the temperatures and sizes of thermal areas is critical for monitoring Yellowstone National Park's hydrothermal activity and for understanding and preserving these spectacular features. The task is challenging, however, given that there are more than 10,000 individual thermal features spread out over large and mostly inaccessible areas within Yellowstone National Park.

Some thermal features are continuously monitored with temperature sensors, such as at Norris Geyser Basin. There, thermal probes are connected via

radio links so that data within the thermal-monitoring network can be viewed anytime. These thermal probes have proven useful for detecting geyser eruptions when visual observations are impossible (because of weather or time of day).

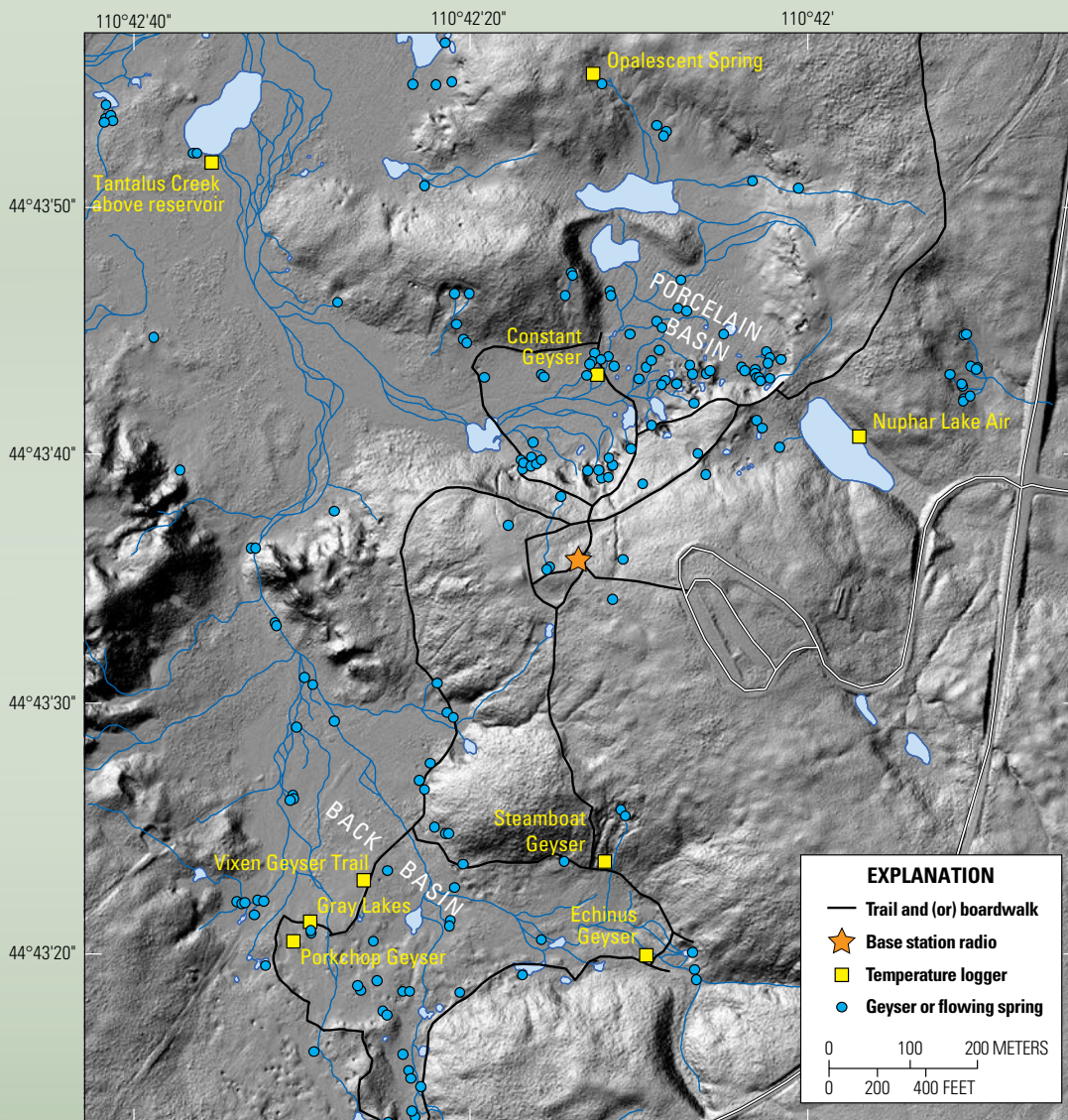
However, temperature probes can only be used to measure the output of a few specific features. To look at overall thermal output of the Yellowstone region, other techniques are employed—for example, tracking the chemistry of Yellowstone National Park's major rivers. Since the hot water from thermal features ultimately ends up in rivers, changes in river chemistry are used to track overall hydrothermal activity. The

most useful chemical indicator is the chloride composition of the river water because hydrothermal water has a high concentration of chloride. In fact, nearly all (95 percent) of the chloride in Yellowstone National Park rivers comes from thermal features. Thus, monitoring the chloride flux (or variability) in the major rivers in Yellowstone National Park provides a reliable way to monitor overall hydrothermal activity. This is now done continuously by automated monitoring stations on all the park's major rivers.

Another method for obtaining broad views of thermal output in the Yellowstone region is to use satellites, which can measure surface temperature and detect changes over time. One of the advantages of satellite-based

thermal-infrared remote sensing is that nearly all the thermal areas in the park can be viewed at once. This broad view comes at a cost—thermal-infrared satellite images tend to have low spatial resolution, with pixels that are 90 meters (about 300 feet) on a side. Nevertheless, thermal-infrared images of Yellowstone National Park have enough detail to make maps of temperature anomalies, which are especially useful in areas that are not easily accessible.

One of the challenges of thermal-infrared remote sensing is that temperature contrasts can be low, and thus challenging to discern. Hot springs and fumarole fields are relatively subtle thermal features compared to extremely hot features like active lavas or fires because the thermal features exhibit sub-boiling to boiling temperatures at the surface in areas that are generally small with respect to the pixel size of thermal-infrared satellite data. During the day, most surface heating comes from the sun, and rocky, sun-facing slopes can mask or exceed the thermal-infrared emittance from thermal areas. Using nighttime thermal-infrared data minimizes the effects of solar radiance and maximizes thermal contrast between thermal and background areas. At night, water bodies are generally warmer

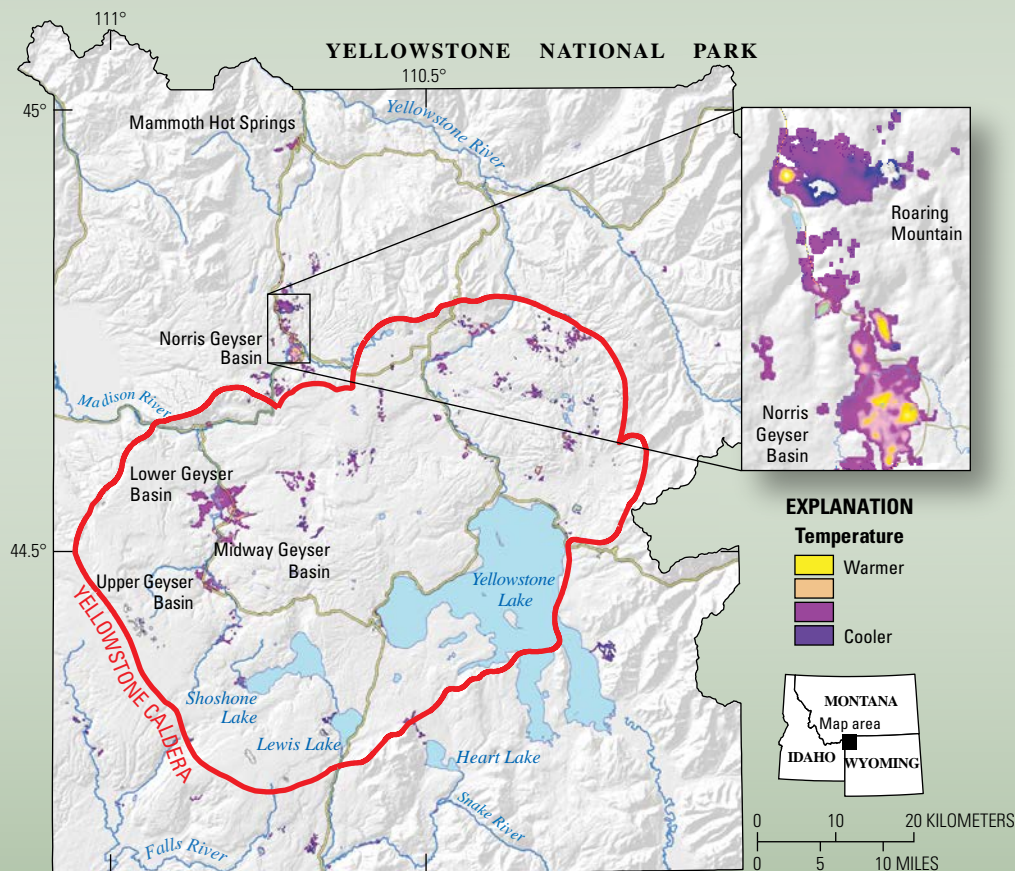
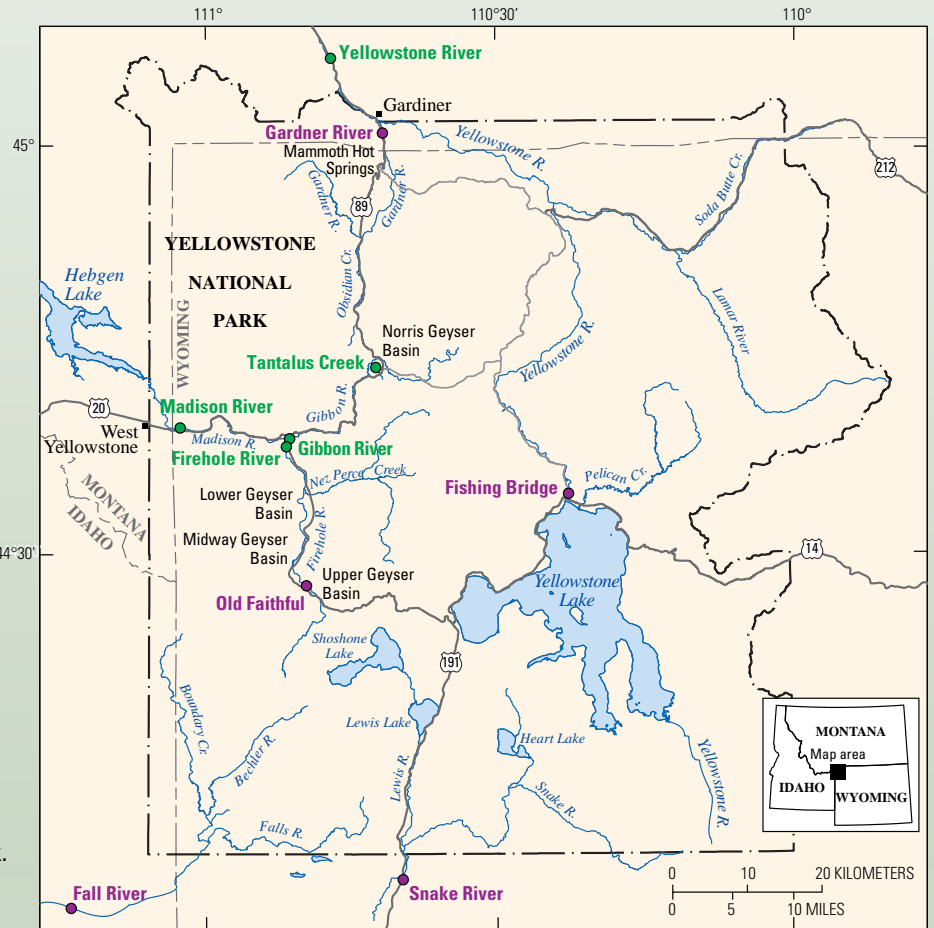


Map of temperature measurement sites in Norris Geyser Basin.



and more radiant than the surrounding land surface and can mask thermal areas adjacent to lakes. In Yellowstone National Park, lakes that do not receive thermal input from nearby hot springs or underwater vents are frozen from late fall through early spring. Therefore, nighttime thermal-infrared data from January through May are preferred. During these times, cloud-free thermal-infrared data can differentiate most thermal areas from ambient background areas because of greater thermal contrast, and these data can be used to evaluate surface thermal metrics, such as geothermal radiant heat flux and geothermal radiative power output. Another advantage of wintertime data is their utility for characterizing thermal input to lakes. These data have revealed the presence of warm vents and springs not previously cataloged into the thermal vent inventory database.

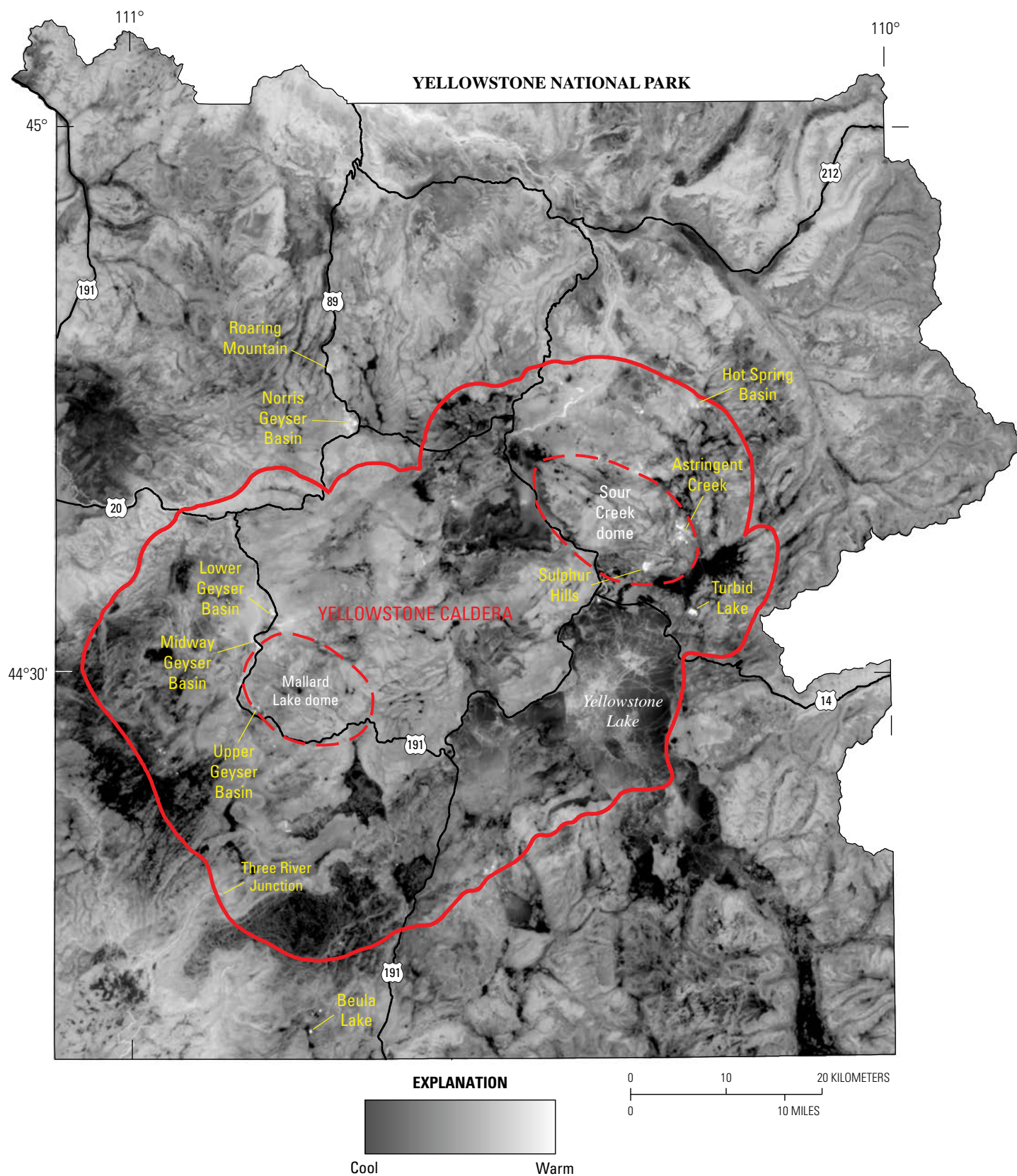
Map showing specific-conductance-monitoring sites for determining chloride flux in rivers that drain thermal areas in Yellowstone National Park. Green stations are telemetered and data from purple stations are downloaded manually.



Base from 30-meter National Elevation Dataset

Satellite thermal infrared temperature anomaly map of Yellowstone National Park's thermal areas based on a Landsat-8 image from April 20, 2017. The warmest areas (yellow) are 20–30 °C (36–54 °F) above background; the cooler areas (purple) are 2–3 °C (4–5 °F) above background. By comparing maps like this for different times, scientists assess changes in thermal areas over time and estimate the total heat output from the Yellowstone region.





**Figure 20.** Landsat-8 nighttime thermal-infrared image of Yellowstone National Park from January 9, 2021. Satellite-based thermal-infrared data show areas of ground that are warmer versus cooler, and they can be used to estimate the geothermal radiative heat output from the Yellowstone magmatic and hydrothermal system. The warmest areas (lightest in shade) in this image are as much as 26 °C (47 °F) above background. Geologic structures are labeled in red; thermal areas are labeled in yellow.



**Table 2.** Total geothermal radiative power output from Yellowstone National Park in the previous 5 years.

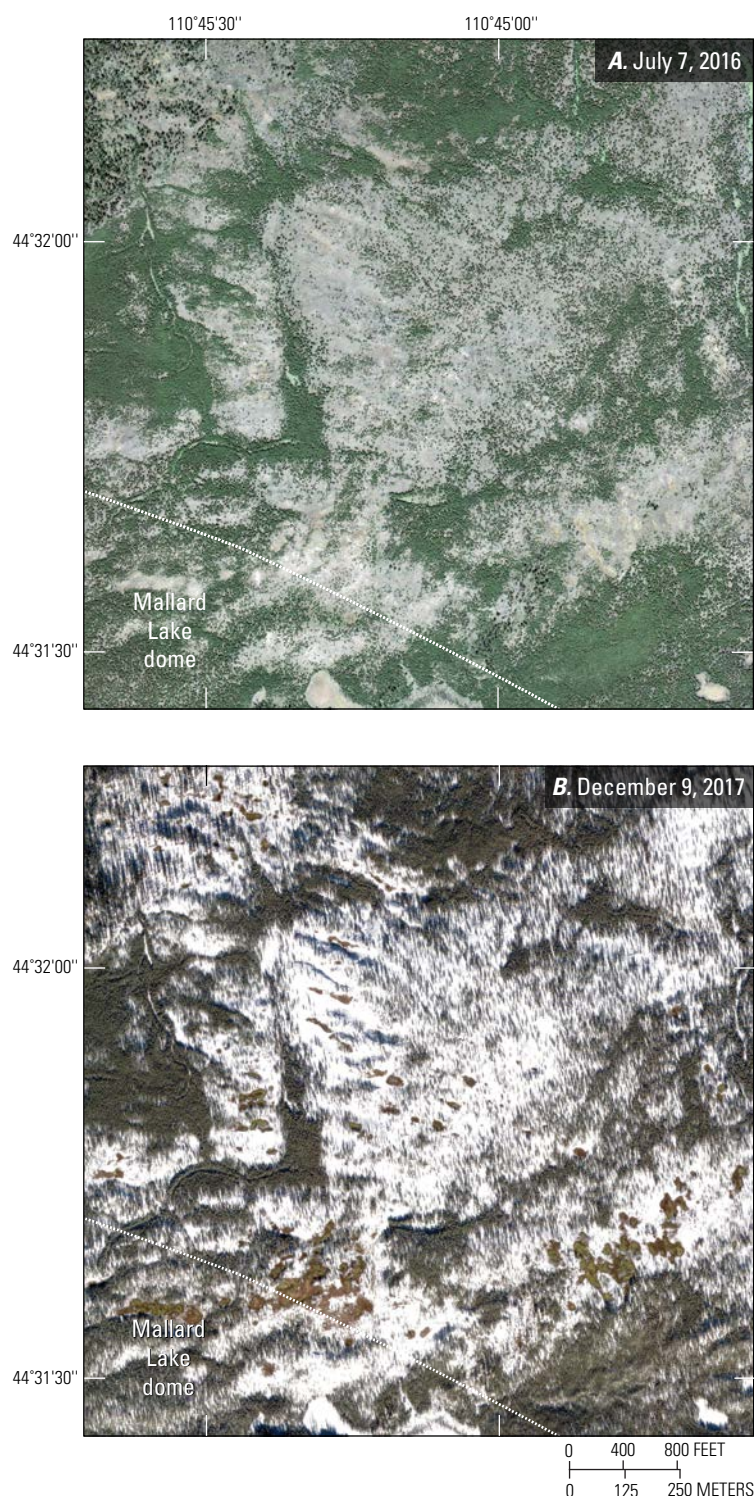
[Revised values were calculated using the new data processing methods; –, not calculated]

Year (acquisition date)	Unrevised geothermal radiative power, in gigawatts	Revised geothermal radiative power, in gigawatts
2017 (April 20)	1.3	1.8
2018 (May 9)	1.3	1.8
2019 (May 12)	1.1	1.3
2020 (March 27)	1.9	2.2
2021 (January 9)	–	2.5

## Recognition of Previously Unmapped Thermal Areas

Mapping thermal areas in Yellowstone National Park is a work in progress, partly because changes occur frequently and also because some thermal areas are in remote wilderness regions that are not easily recognizable from the ground. Satellites with thermal-infrared instruments can directly sense emitted surface radiance and differentiate most thermal areas from the background, but their moderate spatial resolution (90- to 100-meter pixels [about 300 feet]) limits the ability to detect thermal areas that are small or have temperatures insufficiently above background. Routinely acquired high-spatial-resolution airborne and commercial satellite data do not yet have thermal-infrared capabilities, but the sub-meter- to meter-scale pixels in those datasets enable detection and accurate characterization of the visible signs of thermal areas, including vegetation stress and mortality, mineral deposits, hydrothermal alteration, snow-free zones in winter, steaming, bubbling or boiling water, and variable water levels (although even these visible signs are not always obvious).

On the north side of the Mallard Lake resurgent dome, amidst barren rock exposures in an old fire-scarred region, there are numerous small, scattered, isolated thermal areas (fig. 21A). These areas are not big enough or hot enough to be clearly detected with moderate-resolution thermal-infrared data, despite emitting measurable geothermal radiance. Vegetation-free areas with hydrothermal mineral deposits are also difficult to distinguish from surrounding areas, even with high-resolution visible imagery. These thermal areas are warm enough, however, to prevent snow from accumulating on them. High-resolution visible imagery acquired in the winter, when snow is on the ground, shows the thermal areas more clearly (fig. 21B). In fact, these high-resolution visible satellite images are the primary means by which these areas on the north side of Mallard Lake dome were identified. These are not newly emerging thermal areas, like the one identified in 2018 near Tern Lake (Vaughan and others, 2020; YVO, 2021a). Archived remote sensing images going back to the 1980s indicate that these areas have been warm for



**Figure 21.** Satellite images of previously unidentified thermal areas in Yellowstone National Park. *A*, WorldView-3 natural color image from June 7, 2016, of the north side of Mallard Lake dome. *B*, WorldView-2 natural color image from December 9, 2017, of the same area after a snow fall. Some snow-free zones are partly aligned with sun-facing slopes, but the lack of snow and brownish color in unvegetated regions primarily delineates areas with significant geothermal heat.



decades. The regions had not been recorded in the Yellowstone National Park geodatabase of known thermal areas until recently, however, following analysis of high-resolution wintertime visible satellite images. Established but newly recognized areas like these represent a significant portion of the total radiative heat budget of the Yellowstone region, with a geothermal radiative power output on the order of 20 megawatts. More work is needed to characterize these subtle thermal areas, including field work to accurately measure surface and subsurface temperatures, catalog individual thermal features, and measure and sample emitted gases.

## Chloride Flux Monitoring

Measuring the thermal output of Yellowstone Caldera's large magmatic system is not straightforward, as thousands of thermal features are spread across more than 9,000 square kilometers (3,500 square miles). One way to capture and integrate the contributions from this broad area is to monitor river chemistry. Since thermal-water discharge eventually enters a nearby river, rivers act as a collection and delivery system for thermal fluids. Nearly all the chloride in rivers that drain Yellowstone National Park comes from emerging hot-spring water heated underground by underlying magma. Monitoring river chemistry is therefore an important way to track the behavior and overall changes in Yellowstone National Park's hydrothermal system. By monitoring the chloride flux, the hydrothermal discharge and heat flux from the Yellowstone region can be estimated, and variations (both short and long term) can be used to identify changes in the deep hydrothermal system, earthquake activity, geyser eruptions, and other natural events (like floods and the effects of wildfire).

The USGS and Yellowstone National Park have collaborated on chloride-flux monitoring in Yellowstone National Park since the 1970s and have been continually improving the monitoring

network and systems used to quantify solute concentrations and fluxes. Beginning in 2010, the USGS installed stations along major rivers to automatically measure specific conductance (an indication of how well water conducts an electrical current), which is a proxy for the concentration of chloride and other solutes. The use of specific conductance also allows for continuous measurements every 15 minutes.

Monitoring the chloride (and other geothermal solutes) flux in the major rivers draining Yellowstone National Park continued in 2021. Specific conductance measurements were made at monitoring sites along Tantalus Creek and the Madison, Firehole, Gibbon, Snake, Gardner, Yellowstone, and Fall Rivers (see sidebar on monitoring thermal changes on p. 34–35). The current network provides information at several scales (park-wide, watersheds, and individual geyser basins). The Madison, Yellowstone, Snake, and Fall River monitoring sites capture the hydrothermal discharge within their watersheds, and the sum of these four rivers captures the entire hydrothermal discharge from Yellowstone National Park. Additional monitoring sites along their tributaries provide higher resolution and can be used to identify changes at geyser-basin or hot-spring scales. In 2021, a new monitoring station was established along the Lewis River downstream from the outlet of Lewis Lake (fig. 22). The new monitoring site will capture the hydrothermal discharge from large hydrothermal areas and basins within and around Lewis and Shoshone Lakes.

The use of specific conductance as a proxy for chloride requires knowledge of the relation between specific conductance, chloride, and other geothermal solutes ( $\text{SO}_4$ , F,  $\text{HCO}_3$ ,  $\text{SiO}_2$ , K, Li, B, and As), and the relation needs to be confirmed annually. Water samples were collected during two 2021 field trips to assess the solute-specific conductance correlations.

In 2021, the total chloride flux leaving Yellowstone National Park was  $44.5 \pm 4$  kilotons, which was determined

**Figure 22.** Photograph of the Lewis River monitoring site located downstream from the Lewis Lake outlet in Yellowstone National Park. View is looking north (upstream). In 2021, a specific conductance monitoring station was installed at this site. U.S. Geological Survey photograph by Blaine McCleskey in September 2021.





by summing the flux from the Madison, Yellowstone, Snake, and Fall Rivers. This is lower than historical measurements of  $52.6 \pm 4.1$  kilotons (1983–2003 and 2013–2019), although the difference is within the uncertainty of the measurements and calculations. The percentages of the total flux from the Madison (46 percent), Yellowstone (31 percent), Snake (12 percent), and Fall (11 percent) Rivers for 2021 are shown in figure 23A. The 2021 chloride fluxes from every monitoring site were lower than most historical (beginning in 1983) fluxes (fig. 23B). Continued chloride flux monitoring will determine if the observed decrease in hydrothermal discharge from the thermal areas persists.

## Geysers and Hot Springs

Yellowstone National Park hosts thousands of thermal features, including geysers, hot springs, fumaroles, and mud pots. These features are incredibly dynamic, displaying a range of behaviors that vary over time. Some geysers, especially those like Old Faithful that exist in comparative isolation, follow patterns that allow their activity to be forecast. However, most of Yellowstone National Park's geysers, springs, and other thermal features have unpredictable behavior.

### Summary of Geyser Activity and Research in 2021

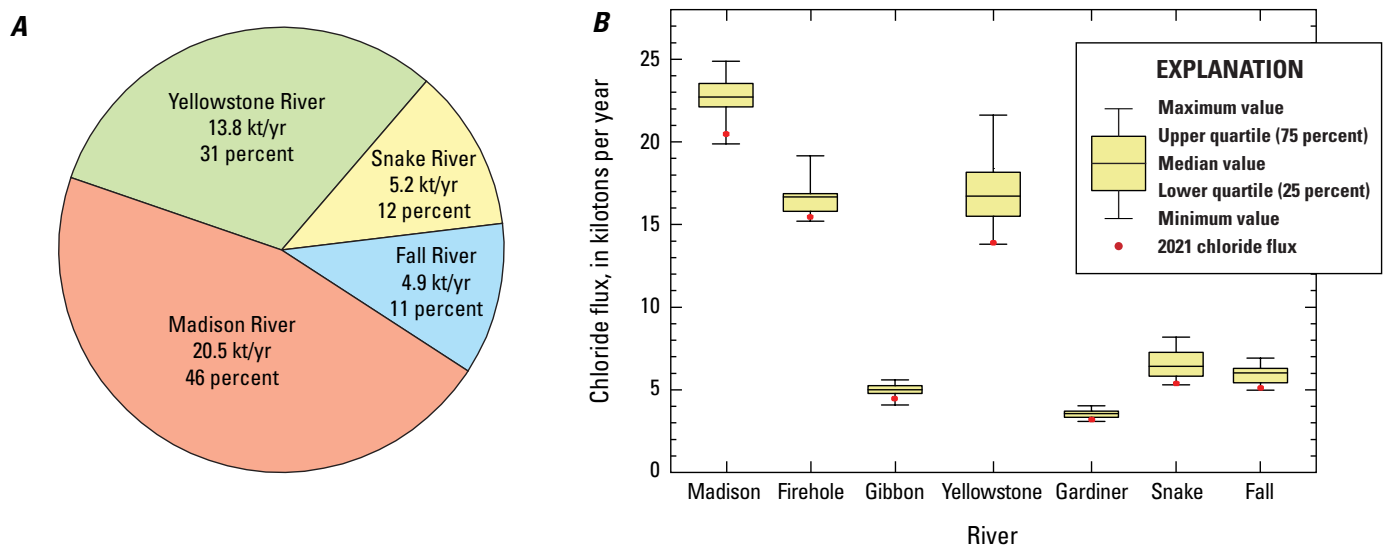
As was true in 2018, 2019, and 2020, the most noteworthy geyser activity in Yellowstone National Park during 2021 continued to be water eruptions from Steamboat Geyser, the tallest active geyser in the world. Fewer eruptions occurred in 2021 compared to the previous 3 years, indicating that the geyser's current period of activity might be waning. Little other geyser

activity of note occurred during the year. Sawmill Geyser, in the Upper Geyser Basin, sprang back to life in June after almost 4.5 years of quiescence. Giantess Geyser, also in the Upper Geyser Basin, erupted once in 2021, after two eruptions in 2020 (those ended a 6.5-year period of inactivity). In May 2020, an unnamed thermal feature in the southwest part of Yellowstone National Park went dry; analysis of satellite data and aerial photographs in 2021 confirmed that this was unusual during the past 20 years and that the feature remained dry through the end of 2020. Efforts by Yellowstone National Park geologists to document thermal features continued in the Upper Geyser Basin and West Thumb Geyser Basin. In addition, new research investigated the structure and composition of geyser cones in Upper Geyser Basin.

### Steamboat Geyser

Steamboat Geyser is a prominent feature of Norris Geyser Basin. The geyser typically experiences frequent minor eruptions that include water splashing as high as a few meters (yards) above the vent and infrequent major eruptions with water columns more than 100 meters (about 300 feet) in height that are separated in some cases by several years. The geyser has a history, however, of entering phases of more frequent major eruptions, as in the 1960s and 1980s, when dozens of eruptions occurred per year, some separated by only days to weeks.

In 2018, Steamboat Geyser (fig. 24) entered a new phase of increased activity, with 32 major water eruptions—a new record for a single calendar year (see YVO 2018 annual report [YVO, 2021a]). That trend continued in 2019 with 48 major eruptions, shattering the record set during the previous year—a record that was equaled with 48 major eruptions in 2020 (see YVO 2019 and 2020 annual reports [YVO, 2021b,c]). In 2021, however, there were only 20 major water eruptions—an impressive number by



**Figure 23.** A, Pie diagram showing the 2021 chloride flux, in kilotons per year (kt/yr), and the percentage of the total flux (44.5 kt/yr) for the four major rivers (Madison, Yellowstone, Snake, and Fall Rivers) that drain the Yellowstone National Park region. Fluxes were measured at gaging locations where the rivers leave the park (see sidebar on p. 34–35). B, Boxplots showing the distribution of chloride flux measurements collected from 1983 to 2021. The 2021 chloride flux for each monitoring site is shown in red.





**Figure 24.** Photograph of Steamboat Geyser displaying steam emissions that are characteristic of periods between major water eruptions. In 2021, 20 major water eruptions occurred—fewer than in the preceding years and with more variable intervals between eruptions. U.S. Geological Survey photograph by Michael Poland, October 12, 2021.

most measures except when compared to the preceding 3 years. It is unclear if the fewer number of eruptions in 2021 is an indication that the current episode of frequent activity is beginning to end.

Each eruption of Steamboat Geyser followed the same general pattern: gradually increasing minor activity over hours to days, culminating in a major water eruption that lasts tens of minutes. A steam phase, lasting for about a day, follows the water eruption, and the minor activity ceases for several days until the buildup to the next eruption begins and the cycle repeats. Also, as is common with Steamboat Geyser eruptions, a pool at Cistern Spring, located about 100 meters (300 feet) downslope, drains within a day after each eruption and then gradually refills over the following days.

The intervals between geyser eruptions in 2021 were longer and more variable than in previous years. The shortest interval between eruptions was more than 6.5 days in April, whereas the longest interval was 65 days during July–September. In previous years, the shortest intervals between eruptions occurred in summer months, presumably owing to abundant groundwater from spring snowmelt (see 2020 YVO annual report [YVO, 2021c]). In 2021, however, the longest intervals were in summer months. The long

durations between eruptions in May–September indicated that the current cycle of frequent eruptions might be gradually ending, but the last 3 months of the year saw eruptions occurring every 2–3 weeks, similar to the start of the year. It seems that Steamboat Geyser is not quite done showing off for park visitors.

The cause of the reactivation of Steamboat Geyser remains ambiguous, despite a thorough investigation of potential causes. Scientists from numerous academic institutions, the National Park Service, and the USGS addressed three fundamental questions related to the onset of the current prolific sequence of eruptions: (1) Why did Steamboat Geyser become active again?, (2) What processes or conditions control the interval between its eruptions?, and (3) Why are its eruption plumes tall compared to those of other geysers?

The study (Reed and others, 2021) analyzed a wide range of datasets to explore triggering mechanisms for Steamboat Geyser’s reactivation and controls on eruption intervals and height. Prior to the renewed activity, Norris Geyser Basin experienced uplift, a slight increase in radiant temperature, and increased regional seismicity, which may indicate that magmatic processes promoted reactivation. However, the geothermal reservoir temperature did not change, no other dormant geysers became active, and previous periods with greater seismic energy release did not reawaken Steamboat Geyser, indicating that none of these characteristics provide a trigger. There is also no obvious correlation among decades of precipitation and river flow rates and periods of frequent eruptions at Steamboat Geyser, arguing against the availability of groundwater as a triggering condition. The reason for reactivation thus remains ambiguous. The study also found no relation between interval between eruptions and erupted volume, implying unsteady heat and mass discharge. Finally, using measurements from geysers worldwide, the study found a correlation between the height of the water eruption and inferred depth to the shallow reservoirs that supply water to eruptions. The study concluded that Steamboat Geyser’s major water eruptions are taller because water is stored deeper there than at other geysers and hence more energy is available to power the eruptions.

Seismic studies of Steamboat Geyser corroborate the hypothesis of a deep plumbing system. Deployments of seismometers around the geyser in 2018 and 2019 (see 2018 and 2019 YVO annual reports [YVO, 2021a,b]) were used to image the seismic source that originates from bubble formation and collapse, providing a four-dimensional view of the geyser’s storage and transport system. The results indicate that Steamboat Geyser’s plumbing system extends at least 140 meters (460 feet) deep—much greater than for other geysers (for example, Old Faithful Geyser’s plumbing system extends 80 meters [260 feet] deep). The geyser’s conduit is approximately vertical to a depth of 120 meters (390 feet), and no obvious connection between Steamboat Geyser and Cistern Spring exists in that depth range, indicating that the two systems are connected through a network of cracks instead of open pipes. The deeper storage of energy within the geyser’s plumbing system probably provides energy to drive more powerful and taller eruptions than is typical at other geysers (Wu and others, 2021).

As in past years, YVO used three indicators to detect eruptions of Steamboat Geyser: (1) increased seismic noise recorded at a seismometer located in the Norris Museum, about



300 meters (1,000 feet) from the geyser, (2) a spike in temperature recorded on the sensor in the geyser's outflow channel, and (3) a spike in discharge recorded at the Tantalus Creek streamgage, through which all water from Norris Geyser Basin hydrothermal features passes. All these data are freely available on the YVO website, accessible at <https://www.usgs.gov/volcanoes/yellowstone>.

## Sawmill Geyser

Sawmill Geyser is part of a group of features between Castle Geyser and Grand Geyser in the Upper Geyser Basin, not far from Old Faithful Geyser. Usually active, Sawmill Geyser experiences frequent eruptions that can last for tens of minutes and reach heights above 10 meters (30 feet). On occasion, however, Sawmill Geyser and several adjacent geysers can enter a pause, with no eruptions, occasionally lasting months (Bryan, 2018). One such pause began in January 2017 and lasted almost 4.5 years. Sawmill Geyser sprang back to life in June 2021, and since that time has erupted often—usually multiple times a day (fig. 25). The unusually long pause of activity in the group of features surrounding Sawmill Geyser appears to have ended.

## Tracking Changes in Thermal Features

The 2020 YVO Annual Report (YVO, 2021c) showcased a thermal pool in the southwest part of Yellowstone National Park that had gone dry. This unnamed thermal feature is located in the Three River Junction thermal area, on the southwest edge of the Yellowstone Caldera (fig. 20). The feature (fig. 26) consists of three interconnected boiling hot spring pools, each 3 to 5 meters (10 to 16 feet) across, with runoff that flows over a colorful terraced sinter mound into Ferris Fork, which feeds into the headwaters of the Bechler River at Three River Junction about 1.5 kilometers (about 1 mile) downstream. Archived airborne and commercial satellite remote sensing data (for example, from WorldView-3, -2, and -1, GeoEye-1, QuickBird-2, and the National Agricultural Imagery Program) going back to 2003 indicate that the typical state for this hot spring was one of abundant runoff (fig. 26A and B). In May 2020, however, an observer on a National Park Service fire cache flight noted that these pools were nearly empty, with no bubbling, boiling, or steaming, and no hot water overflow (YVO, 2021c). The vibrant colors were absent, exposing only tannish hydrothermal mineral deposits (fig. 26F).

The observed drying of this thermal feature raises several follow-up questions. When did this change happen? Has it happened before? It is a normal seasonal fluctuation, a response to drought, changing climate, or something else? Did it return to its typical state over the winter of 2021–2022? To investigate these questions, YVO scientists explored archived high-resolution airborne and commercial satellite imagery. In 2019, there were two clear images, acquired on July 30 and August 28, which showed the three thermal pools full of blue water and some overflow into the river (fig. 26C and D). In the August 28 image, however, the largest pool did not appear to exhibit the vigorous boiling in the center that had been evident in all the previous images. This



**Figure 25.** Photograph of Sawmill Geyser in eruption on July 23, 2021. Old Faithful Inn is in the background. National Park Service photograph by Morgan Nasholds.

reduced boiling could be the first indication of the impending drying out, which was initially observed in May 2020.

Throughout 2020, numerous clear images were acquired over this area with Maxar Technology's suite of satellites (WorldView-1, -2, and -3). The changes to this feature that were initially observed in May 2020 also were clearly seen in an image from April 22, 2020 (fig. 26E), and June 15, 2020 (fig. 26G). In earlier wintertime images from January and February 2020, the low sun angle and shadows obscured a clear view of the water level in the pools, but the area was clearly warm enough to be free of snow, although less steam was observed than previously. Whether the pools were already dry at this point could not be determined. In the most recent clear image, from October 7, 2020, there appeared to be more water filling the two smaller pools (fig. 26H). It may be that the feature was in the process of





**Figure 26.** Satellite images of an unnamed thermal feature in the Three River Junction thermal area, southwest Yellowstone National Park (see fig. 20 for location). *A*, WorldView-3 natural color image from September 25, 2014. *B*, National Park Service (NPS) oblique aerial photograph from ~2017, exemplifying the feature's typical appearance at that time. *C*, WorldView-3 natural color image from July 30, 2019. *D*, National Agricultural Imagery Program (NAIP) natural color image from August 28, 2019. *E*, WorldView-2 natural color image from April 22, 2020. *F*, National Park Service oblique aerial photograph from May 2020 showing the nearly empty pools. Note that the thermal feature across the river was still hot and steaming as usual. *G*, WorldView-3 natural color image from June 15, 2020. *H*, WorldView-3 natural color image from October 7, 2020. In this image, it appears that the three pools may be filling with water. All images are approximately the same scale. Note that National Park Service photographs in parts *B* and *F* are not oriented with north at the top.



returning to its more typical state, or the observation may represent a seasonal fluctuation in water level. Unfortunately, no clear high-resolution remote sensing images were acquired in 2021. A visit by a Yellowstone National Park backcountry monitoring crew in February 2021 observed “tepid, standing water” (H. Robison, National Park Service, written communication, 2021). It remains unknown whether this feature has returned to its prior state. Regardless, the early 2020 draining and cooling of this feature appears to be a unique event over the past 20 years and remains unexplained. In the future, a combination of field and aircraft observations and commercial satellite images will be an effective way to continue monitoring changes to this and similar remote backcountry thermal features.

## Structure and Composition of Geyser Cones

Cone geysers typified by Old Faithful are composed of sinter—a form of opal that precipitates from the alkaline thermal waters released by geyser eruptions. The sinter contains microbial films that exist at extreme temperatures and thus may hold clues to the origin of life on Earth. In addition, the chemical composition of the sinter can provide information about the composition of thermal waters and the characteristics of subsurface geology.

During 2018–2020, USGS, Yellowstone National Park, and university scientists collected sinter samples and photographs of Castle and Giant Geysers (fig. 27) in the Upper Geyser Basin. The goals of this study (Churchill and others, 2021) were to: (1) characterize the size and structure of large geysers in Yellowstone National Park, (2) understand the physical chemical changes in the sinter over time owing to dehydration, and (3) investigate the chemical composition of sinter deposits and how the composition relates to that of the thermal water from which the silica sinter forms.

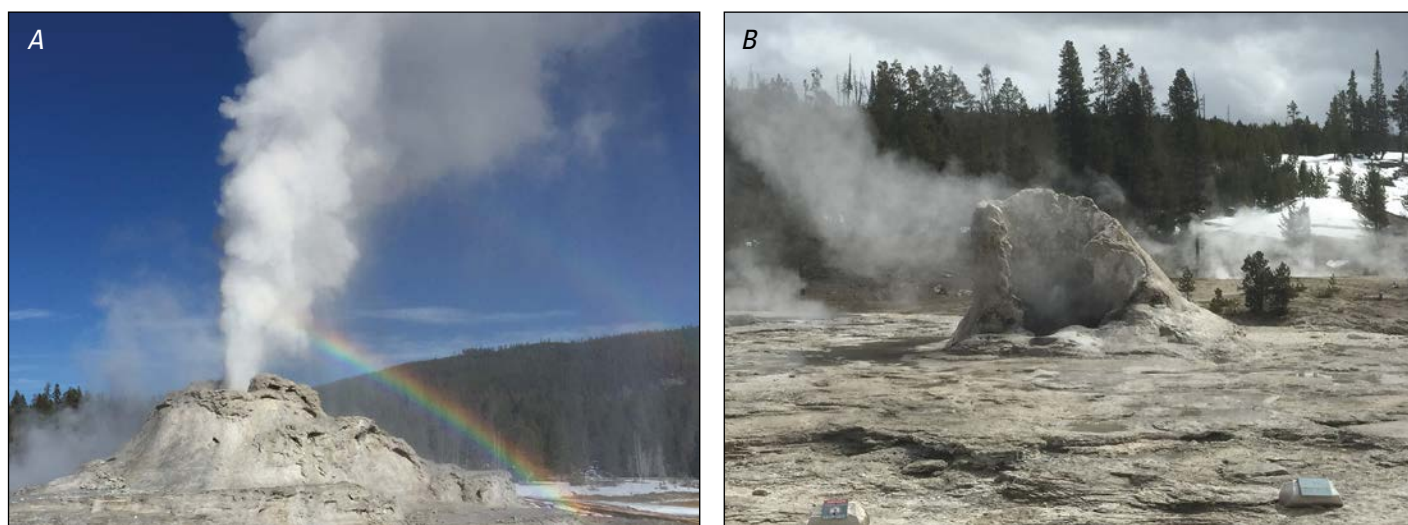
The photographs were used to construct high-resolution, three-dimensional models of the geyser cones (fig. 28). The models, available online at <https://irma.nps.gov/DataStore/>

[Reference/Profile/2273777](https://irma.nps.gov/DataStore/Reference/Profile/2273777) (Giant Geyser) and <https://irma.nps.gov/DataStore/Reference/Profile/2278667> (Castle Geyser), were used to calculate the approximate mass of sinter that makes up the cones—about 2,000 metric tons for Giant Geyser and about 5,000 metric tons for Castle Geyser. Given that Yellowstone National Park’s geyser cones grew since the end of the most recent ice age about 14,000 years ago, the long-term plausible rates of sinter deposition for Castle Geyser are an impressive 470 to 940 kilograms (about 1,000–2,000 pounds) per year.

In terms of compositions, young, opaline sinter with a high water content was found to have higher concentrations of major and trace elements (notably arsenic, antimony, rubidium, gallium, and cesium) than older, dehydrated sinter. In addition, rare earth element concentrations in the sinter are two to three orders of magnitude higher than in the thermal water from which they are deposited, indicating that such elements are preferentially deposited in the sinter and not carried away by the waters after they reach the surface. Sinter samples with the highest concentrations of rare earth elements are also rich in organic material, implying that microorganisms take in these elements or that organic molecules are favorable to bonding with these elements.

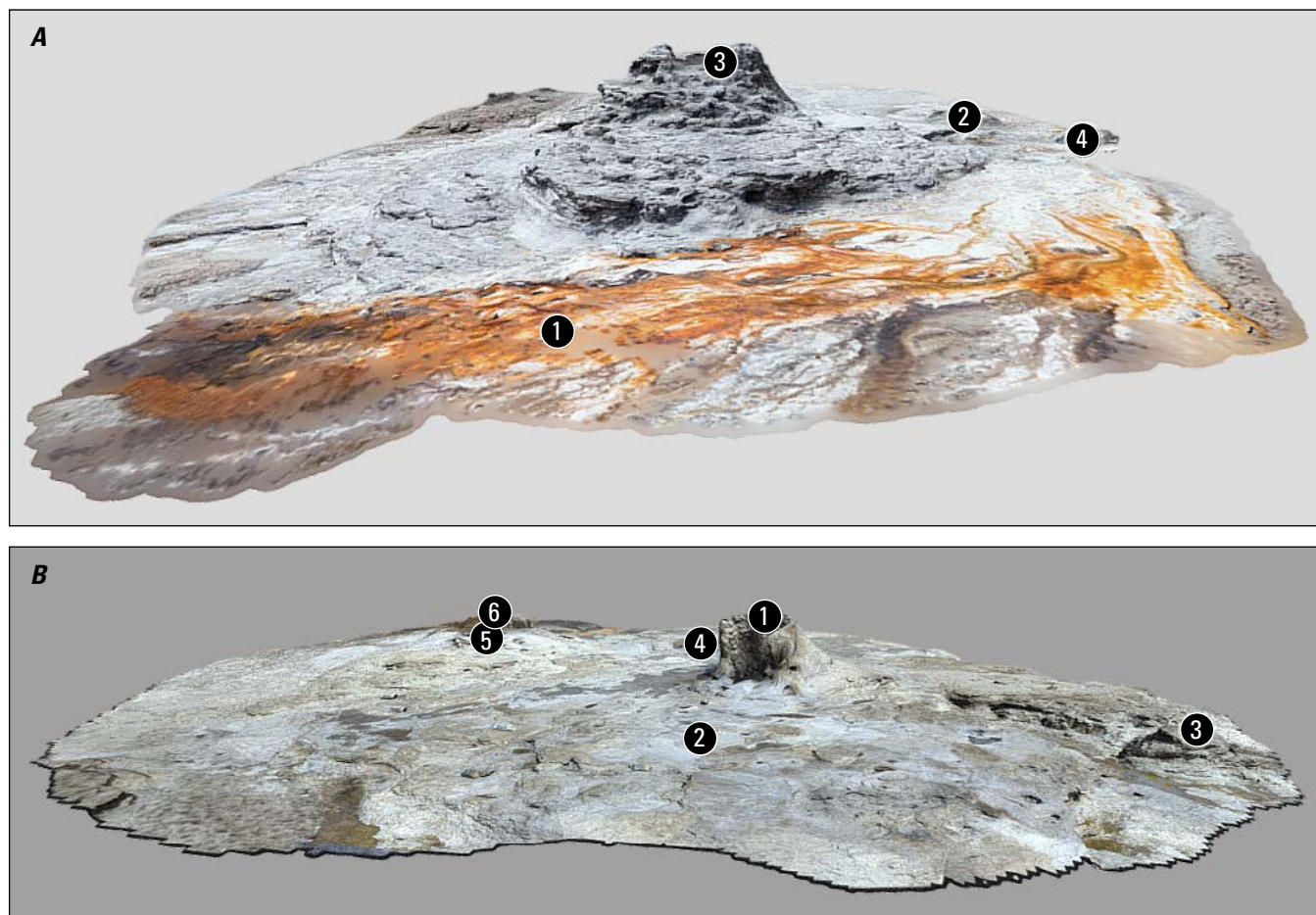
## Hydrothermal Feature Survey

Over the 2021 field season, the Yellowstone National Park Geology Program continued its multi-year effort to visit and document every hydrothermal feature in the park, building on a previous survey completed during 1998–2007. In 2018–2019, the hydrothermal feature inventory project documented more than 1,100 features in the Norris Geyser Basin south of the Gibbon River, as compared to 493 in the previous inventory. This difference does not reflect an increase in the number of thermal features, but rather a change in inventory protocol—specifically, the types of features that were included in the inventory. Smaller features not included or grouped with other features during the first survey have been classified as separate features in the second



**Figure 27.** Photographs of Castle (A) and Giant (B) Geysers in Upper Geyser Basin of Yellowstone National Park. Sinter samples were collected from these geyser cones in an attempt to determine their age. U.S. Geological Survey photographs by Shaul Hurwitz on November 5, 2019 (Castle Geyser) and April 15, 2018 (Giant Geyser).





**Figure 28.** Screenshots of three-dimensional models of Castle (A) and Giant (B) Geysers constructed using structure-from-motion photogrammetry. Numbered features on the Castle Geyser model are: (1) bacteria mat, (2) Tortoise Shell Spring, (3) the vent of Castle Geyser, and (4) the informally named Gizmo geyser. Numbered features on the Giant Geyser model are: (1) cone of Giant Geyser, (2) location of a physical scale bar used for geolocation, (3) the informally named Turtle geyser, (4) Mastiff Geyser, (5) Catfish Geyser, and (6) Bijou Geyser.

survey. Inventory efforts shifted to the Upper Geyser Basin in 2019, where 1,336 features were documented compared to 668 features in the same area during the previous inventory project, the increase in numbers again because of a change in methodology.

During 2021 field seasons, the Geology Program finished the Upper Geyser Basin survey, identifying more than 2,000 hydrothermal features. Once finished with the Upper Geyser Basin, effort shifted to the West Thumb geothermal areas. The Geology Program team focused their work on upper Potts Hot Spring Basin, which is approximately 1.5 kilometers (1 mile) north of the boardwalks in the West Thumb Geyser Basin.

The new inventory will support the Yellowstone National Park's mission to preserve and protect natural resources for the enjoyment and education of present and future generations. It also will provide a more detailed baseline against which future changes can be compared.

In addition to the park-wide inventory, Yellowstone National Park scientists are performing monthly assessments of 22 individual thermal features, including, for example,

Dragons Mouth Spring in the Mud Volcano area, Morning Glory Pool in the Upper Geyser Basin, Cistern Spring in Norris Geyser Basin, and Excelsior Geyser in Midway Geyser Basin. This indexing program involves collecting monthly measurements of pH, conductivity, and temperature, as well as acquiring thermal imagery. Comparison of how these parameters change over time could be useful in identifying variations in hydrothermal activity in various parts of Yellowstone National Park. Yellowstone National Park scientists, in collaboration with the Geyser Observation and Study Association, also maintain a network of nearly 100 temperature logging instruments installed at features throughout the park. Special deployments of temperature logging instruments in 2021 included thermal features of the Heart Lake and Shoshone Geyser Basins.

The Yellowstone National Park Geology Program also performed the initial installation of telemetered thermal sensors in the Upper Geyser Basin late in the 2021 field season. Thermal sensors were placed in the runoff channels



of Old Faithful, Castle, Beehive, Grand, and Lion Geysers. Program members are testing the telemetered array of thermal loggers and hope to have the system fully operational in the spring of 2022. Once operational, the array of loggers will send out geyser data every 10 minutes.

## Communications and Outreach

Because of the COVID-19 pandemic, in-person outreach activities were severely limited, and most outreach efforts in 2021 were necessarily remote or virtual. YVO continued to produce products that have now become traditional, including monthly video updates of activity (posted on “USGSVolcanoes” Facebook and Twitter pages, the USGS YouTube channel, the USGS Multimedia Gallery [downloadable], and the multimedia section of the YVO website) and weekly Yellowstone Caldera Chronicles articles, which are posted to social media pages and published by several regional news outlets. In addition, several YVO scientists contributed expertise to planned upgrades to visitor center displays in Yellowstone National Park.

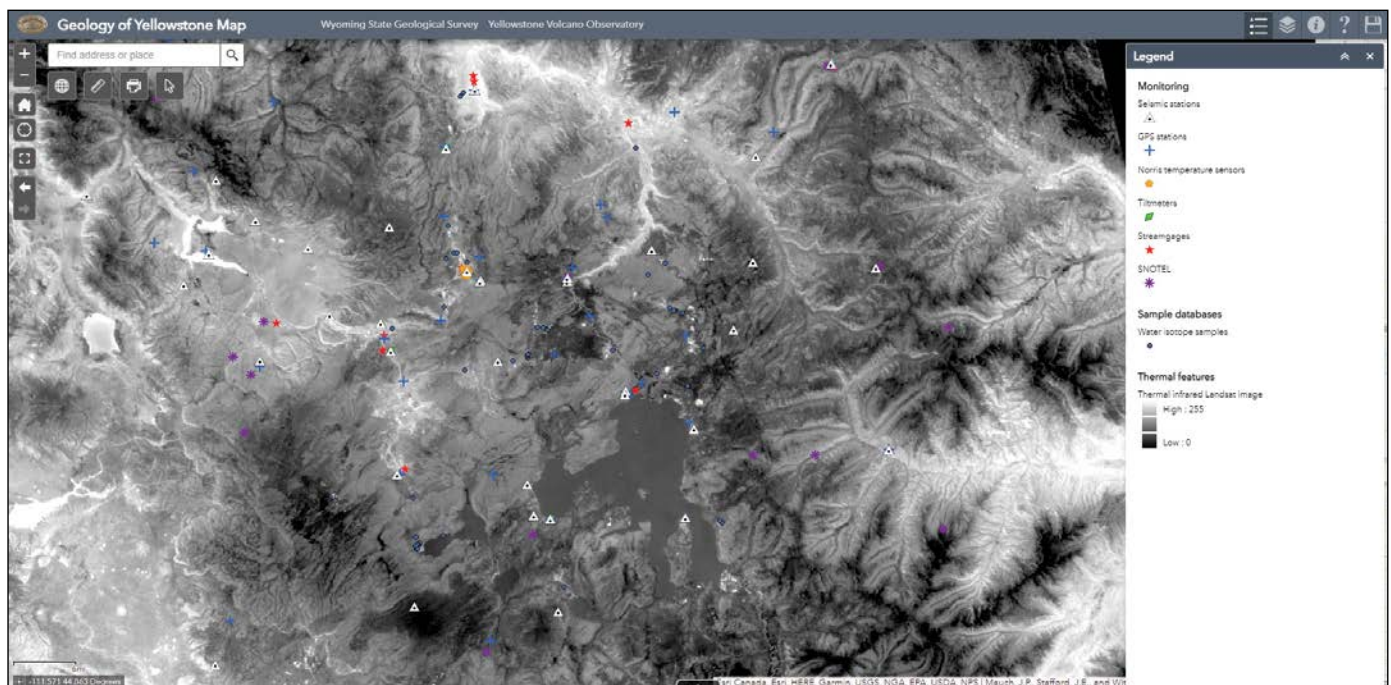
In November, YVO Scientist-in-Charge Michael Poland gave a presentation entitled “Busting Myths About One of the Largest Volcanic Systems in the World: The Top 10 Misconceptions about Yellowstone Volcanism” as part of the USGS public lecture series. The virtual presentation highlighted the origins of, and attempted to correct, the most common misconceptions about the Yellowstone volcanic system. The lecture is available online for public viewing

at <https://www.usgs.gov/news/state-news-release/media-advisory-busting-myths-about-one-largest-volcanic-systems-world-live>.

## Online Geology of Yellowstone Map

Launched in the summer of 2020, the online Geology of Yellowstone Map (fig. 29) continues to be a one-stop shop for digitally exploring the Yellowstone region’s rich geologic history and landscapes. The Wyoming State Geological Survey (WSGS) developed the map to compile the abundance of publicly available geospatial information on the regional geology into an accessible, interactive, and visual format that is useful for scientists, managers, and park visitors alike. The map displays more than 100 layers encompassing bedrock geology, thermal features, hydrography, scientific monitoring stations, seismicity, and much additional information. A simple web interface allows users to view the map with only an internet connection and without the need for specialized software. The Geology of Yellowstone Map can be found on the WSGS homepage (<https://www.wsgs.wyo.gov>) under the “Interactive Maps” panel.

The WSGS updates the map as new data are released, and the map is intended to be a growing chronicle of geologic and geospatial information for the Yellowstone region. In late 2021, the WSGS added new map layers for seismic stations, GPS stations, temperature sensors, tiltmeters, streamgages, snow telemetry sites, water isotope samples, thermal-infrared satellite imagery, and geomorphic landforms. The University of Utah, USGS, National Park Service, UNAVCO, and other YVO



**Figure 29.** Screenshot of the online Geology of Yellowstone Map showing some of the layers that were added in 2021. Shown here are the locations of various monitoring instruments and water sample sites overlain on a thermal-infrared satellite image.



collaborators provided the data for these additions. In 2021, the WSGS made monthly updates incorporating data from regional seismic activity. These monthly updates will continue in 2022, when the WSGS also plans to add map layers from several recent USGS data releases. Map users are encouraged to check back regularly as these updates are published.

## Summary

Despite the decrease in activity compared to the previous 3 years, Steamboat Geyser continued to impress visitors with 20 major water eruptions in 2021. This episodic activity is typical of many geysers in Yellowstone National Park, as demonstrated once again in 2021, when Sawmill Geyser returned to its usual pattern of multiple eruptions per day after about 4.5 years of quiescence. Monitoring measurements indicate background levels of seismicity, deformation, and thermal emissions. The number of located earthquakes (2,773) was the most since 2017, when 3,427 earthquakes were located, but the 2021 value was still not significantly different from the average number of annual located events. GPS measurements indicated no significant deformation at Norris Geyser Basin throughout the year, and Yellowstone Caldera continued to subside at rates of a few centimeters (about 1 inch) per year, as it has since 2015. One noteworthy change in deformation style was detected by satellite radar, which documented about 1 centimeter (0.4 inch) of uplift centered on the north side of the caldera, south of Norris Geyser Basin, between late 2020 and late 2021. The deformation strongly resembles that which occurred during 1996–2004 but is yet too small to be strongly apparent in nearby continuous GPS stations. Heat flux estimates from both satellite imagery and river chemistry indicate no major changes with respect to previous years.

The COVID-19 pandemic limited field work in 2021, although critical equipment maintenance and deployments and several scientific studies were still carried out. Temporary deployments of seismometers in Norris and Upper Geyser Basins collected information that will be used to better understand geyser plumbing systems, and a new continuous gas-monitoring station—the first of its kind in Yellowstone National Park—was deployed near Mud Volcano in July. Geologic investigations focused on better understanding the age and history of hydrothermal explosion craters in the Lower Geyser Basin, revising geologic maps in the areas around Mount Everts and the Sour Creek resurgent dome, improving age constraints on post-caldera rhyolite lava flows, and investigating the sources of hydrothermal travertine within Yellowstone Caldera. Additional sedimentary cores were collected from Yellowstone Lake to better constrain the characteristics and extent of lake-bottom hydrothermal activity and triggers for hydrothermal explosions. New research results will be highlighted in future editions of YVO's weekly series of online articles, Yellowstone Caldera Chronicles, which can be accessed at <https://www.usgs.gov/volcanoes/yellowstone/caldera-chronicles>, as well as in annual reports, monthly updates and videos, and public presentations.

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National Park Service photograph showing bison in Lamar Valley by Diane Renkin.









National Park Service photograph showing Castle Geyser and the Milky Way by Neal Herbert.





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